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CHARACTERISATION AND APPROPRIATE DEVELOPMENT OF SITES ON DOLOMITE

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Characterisation and appropriate development of sites on dolomite

by

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ABSTRACT

This document attempts to give broad and consequently simplified background information pertinent to understanding the significance of the need to characterise the stability of dolomitic land prior to development. A single framework of reference for the execution of stability investigations is proposed. This proposal was formulated after reviewing existing classification systems, investigation procedures and stability investigation reports. In addition, extensive consultations were held with engineering geologists, geotechnical and civil engineers, geohydrologists, hydrologists and town and regional planners.

This proposed approach is entitled the "Method of Scenario Supposition" and essentially provides a general set of factors to be utilised as a check list defining a deductive process and culminating in a stability characterisation. The factors for the characterisation of the risk of doline and sinkhole formation have been defined as has associated terminology. This characterisation process culminates in the expression of the stability in terms of the risk of doline and sinkhole formation. Proposals are made concerning appropriate development in relation to identified risk categories.

The method of scenario supposition is reviewed in the context of a case study area on a non-dewatered dolomitic aquifer and in the context of twenty smaller, randomly selected, case study areas in compartments subjected to artificial drawdown of the groundwater level.

Karakterisering en toepaslike ontwikkeling van terreine op dolomiete

DEUR

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SAMEVATTING

Hierdie dokument poog om bree en derhalwe vereenvoudige agtergrondinligting te verskaf ten einde die belangrikheid van stabiliteitskarakterisering van dolomietterreine voor ontwikkeling te beklemtoon. 'n Enkelvoudige verwysingsraamwerk word vir die uitvoer van stabiliteitsvaluering voorgestel. Hersiening van die bestaande klassifikasiesisteme, ondersoekprosedures en stabiliteitsondersoekverslae is as grondslag gebruik vir die formulering van hierdie voorstel. Breedvoerige onderhoude met ingenieursgeoloe, geotegniese en siviele ingenieurs, geohidroloe, hidroloe asook stads- en streeksbeplanners is gevoer om die voorgestelde begrippe te toets.

Die voorgestelde benadering staan bekend as "die metode van scenario-veronderstelling" en bevat 'n aantal faktore as kontrolelys vir 'n deduktiewe proses van stabiliteitskarakterisering. Die faktore vir die karakterisering van die risiko vir doliene- en sinkgatvorming, asook die geassosieerde terminologie word gedefinieer. Die karakterisereringsproses het die uitdrukking van stabiliteit in terme van die risiko van doline- en sinkgatvorming ten doel. Voorstelle rakende toepaslike ontwikkeling met betrekking tot risikokatergiee word gemaak.

Die metode van scenario-veronderstelling is getoets in die konteks van 'n gevallestudiegebied in 'n nie-ontwaterde dolomitiese grondwaterkompartement sowel as in twintig kleiner ewekansig gekose gevallestudiegebiede in kompartemente waarin die grondwatervlak kunsmatig verlaag is.

TABLE OF CONTENTS

FIGURES

TABLES

PLATES

1. INTRODUCTION

Since the early sixties, the term dolomite land has been used by the Geological Survey of South Africa and the engineering geological fraternity to denote land which is underlain by dolomite at a depth of less than 100metres. This term is also applied to areas where the dolomite bedrock is overlain by younger formations; for example, rocks of the Pretoria Group, Karoo Sequence or Quaternary aeolian sands.

Although dolomite land constitutes only about 5 percent of the surface area of the Transvaal, a major portion of the area covered by the guideplan announced by the Minister of Constitutional Development and Planning during June 1988, is in fact underlain by dolomite (Figure 1). This area is earmarked for urban development and, hence, is destined for the rapid urbanisation of a large portion of the present rural population. The spatial distribution of the dolomite with respect to existing urban and mining centres has inevitably led to development encroaching on the dolomite girdle that surrounds the core region of the Pretoria-Witwatersrand-Vereeniging complex.

It is common knowledge that the process of urbanisation is occurring at an accelerating rate in the greater Pretoria-Witwatersrand-Vereeniging area. A manifestation of this process is the burgeoning population within existing, already overpopulated areas and the rapid development of informal settlements (Tables 1 and 2).

TABLE 1: Typical population densities in towns located on dolomite.

TOWNSHIP	POPULATION	FORMALLY HOUSED	PERSONS PER 250 SQ. M. ERVEN	INFRA-STRUCTURE
BEKKERSDAL	50 000	24 000	38	POOR
THOKOZA	140 000	70 000	25	POOR
KATHLEHONG	500 000	120 000	25	POOR
DUDUZA	50 000	22 500	13	POOR
KWA-THEMA	145 000	64 000	14	POOR
VOSLOORUS	112 000	-	13	GOOD

(Information source Mashabala (1988) and Hansard (R) September 1977.)

Figure 1: Guideplan of the Pretoria-Witwatersrand-Vereeniging area (Department of constitutional Development and Planning -1988).

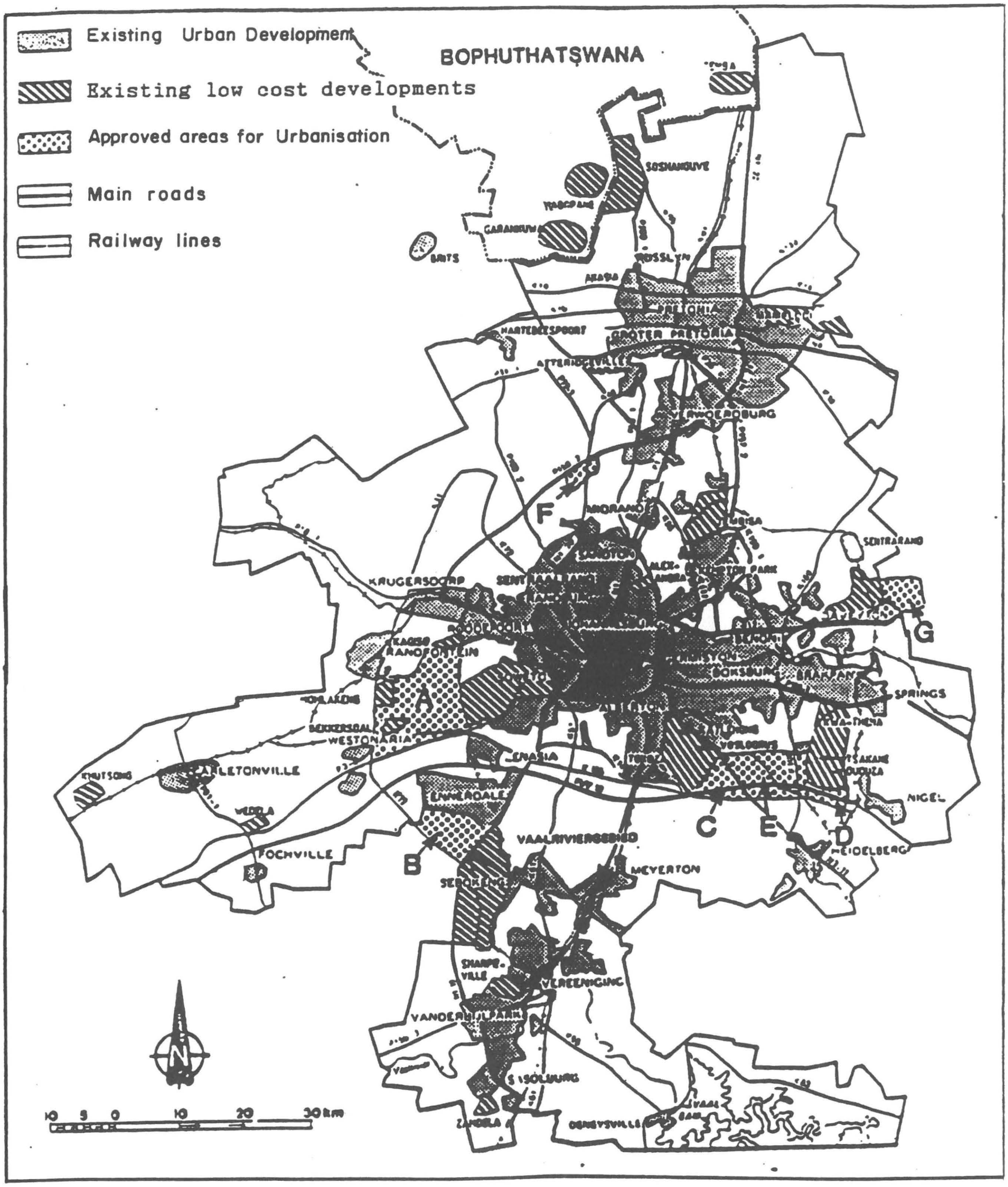


Table 2: Example of townships partially or totally located on dolomite.

Portions of Alberton
Portions of Boksburg
Botleng
Carletonville
Clayville
Portions of Daveyton
Delmas
Portions of Duduza
Khutsong
Portions of Krugersdorp
Laudium
Lenasia
Portions of Meyerton
Olifantsfontein
Portions of Vereeniging
Verwoerdburg
Vosloorus
Westonaria

Research by Mashabala (1977) indicates that in certain townships located on dolomite in the Pretoria-Witwatersrand-Vereeniging complex the number of inhabitants per stand is between thirty and forty. The stands are usually less than 300 square metres in extent. In Bekkersdal there is estimated to be an average of six backyard shacks on each of the properties of the 1 242 conventional houses. As indicated in Table 1 there are in excess of 70 000 people without conventional housing who live in make-shift structures in backyards or shack settlements. According to the Urban Foundation, the poorest fifth of the population can afford only up to R3 500 towards housing costs. "Site costs" do not include the costs of improvements or service charges (Cosser 1989). The conclusion is, therefore, that overcrowding will continue and in fact be exacerbated by increasing population pressures. In many instances the result is unplanned, sometimes poorly structured homeless camps and an almost total human coverage of the landscape. In this context it must be noted that whenever urban development occurs on dolomite, man is exposed to the potentially devastating side effects of his activities; particularly if stability investigations are not competently conducted and appropriate precautionary measures implemented. Activities associated with development normally result in a disturbance of the metastable conditions prevalent in the virgin dolomite environment. Natural drainage patterns are artificially altered, water concentration is induced, soil materials are disturbed when services are installed, water bearing services concentrate water in the ground and the ground water situation may be dramatically altered. In view of the costs of safely developing towns on dolomite it is essential that the poorest sectors of the community are allocated in the engineering geologically least problematical land whenever possible.

The spectacular and tragic consequences of man's activities in the dolomite environment were mirrored in the news headlines of the early sixties. People awoke to the stark realities of the risk of living on dolomite. During the past 30 years a total of 38 people were interred in sinkholes, property has been damaged and the market value of properties on dolomite plunged. It is this historical perspective combined with the rapid urbanisation of dolomite land that underscores the need for the careful evaluation of the stability of sites prior to development. The Unit for Applied Studies on Dolomite at the S.A. Geological Survey has found that more than 96 per cent of 380 sinkholes, recorded in a small area of essentially middle to upper class residential development south of Pretoria were artificially induced as a consequence of man's activities. It is imperative that, as pressure mounts for dolomite land to be made available for residential development, particularly low cost, high density housing, the standard of investigations and precautionary measures are not ignored or relaxed. The public has to have confidence that there are no hidden dangers attached to the land it has purchased once a township is proclaimed. Given the growing development pressures, the standard of stability investigations has increasingly caused concern as has the lack of standardisation in methodology, terminology and reporting procedure. Of great concern also is the level of awareness pertaining to the dolomite issue amongst architects, planners and engineers responsible for the design of townships and the implementation of appropriate precautionary measures. These precautionary measures and the township design are fundamental in ensuring the long-term safety and well-being of the populace and viability of a community.

Given the concerns expressed above, this study was initiated with the following principal objectives:

- principally to enhance the standard of dolomite stability assessment by consultation with experts in this field and by research.

- to review general information pertaining to dolomite, spatial distribution of dolomite and consequences of development on dolomite.

- to review standards, ordinances and reporting and procedural requirements for stability investigations. The reviewing of an excess of 500 investigation reports has highlighted gross inadequacies in the thoroughness of many of these documents in terms of recording, investigative and concluding procedures. Legal scrutiny confirms this assessment. Consequently a diverse cross section of the engineering geological and geotechnical fraternities were consulted and proposals on report content gathered. Guidelines are provided on this aspect in this document. It must be emphasised that the reporting process is viewed as a fundamental ingredient in the stability evaluation process. If the methodology of stability characterisation is not accurately recorded, the investigation has not been competently completed. The report must be able to withstand legal scrutiny. Proposals are made in this thesis concerning the information believed to be important for record purposes.

- to propose and motivate a single framework of reference for the execution of stability evaluations. This proposal was developed after reviewing existing classification systems, investigation procedures and stability investigation reports. In addition, this framework embraces the experience derived from deliberations with consultants, field visits to sites under investigation, viewing large numbers of sinkholes/subsidences, inspecting caves and the execution of stability investigations. This approach, entitled the "method of scenario supposition" essentially provides a general set of factors to be utilised as a check list, defining a deductive process and culminating in a stability characterisation. The factors for the characterisation of the risk of sinkhole and doline formation are defined as is the associated terminology.

The method of scenario supposition culminates in the characterisation of the stability of the site in terms of the risk of a doline and certain sizes of sinkholes forming.

- to apply the method of scenario supposition in the context of a dewatering and non-dewatering scenario in order to verify the validity of applying this evaluation technique to dolomitic sites. Verification is largely based on comparing the predictions of the methodology to actual stability information (recorded ground movement events) by back-analysis.

- to propose and motivate the need for appropriate development in relation to the risk characterisation of dolomitic land. As urban development normally results in a disturbance of the metastable conditions prevalent in the dolomite environment, the basic design of the township is a key element in the overall strategy to minimise the impact of the proposed development on the environment. The particular type of development selected in relation to the risk is critical to the safe, successful and long term viability of a project.

This study emphasises that development on dolomite is feasible but it is vital that appropriate development is considered in relation to risk, in the process of land allocation.

2. GENERAL INFORMATION PERTAINING TO DEVELOPMENT ON DOLOMITE

This section is devoted to providing the reader with a rudimentary background perspective on the dolomite issue.

2.1 Definition of dolomite land.

The Geological Survey has, since the early sixties, utilised the term "dolomite land" as referring to land underlain directly or at shallow depth by the rock type dolomite. "Shallow depth" is taken to imply any depth less than 100 metres. This definition thus includes land that is underlain directly by Karoo Sequence, Pretoria Group sediments or younger deposits, but at depth, by dolomite.

2.2 Why is dolomite unique?

Dolomite is a rock composed mainly of the mineral of that name which is a calcium magnesium carbonate (CaMg(C03)2). The structure of the dolomite may be presented as layers of calcite (CaC03) and magnesite (MgC03) (Deer et al, 1966). In ordinary dolomite, the proportion of CaC03 to MgC03 is 1:1. Calcium may, however, be substituted for magnesium up to a Ca:Mg ratio of 1:5.

Theoretically, therefore, dolomite is a simple carbonate of magnesium and calcium as defined above. A considerable content of iron and manganese may be present. Iron, manganese and magnesium are diadochic in the structure of dolomite. These elements have, therefore, the ability to occupy the same lattice position in the crystal structure. Consequently iron and manganese may be substituted for magnesium in the dolomite lattice.

Dolomite is distinguished from other rock types due to its relatively high solubility. Rainwater and percolating groundwater is enriched with carbon dioxide to form a weak carbonic acid as follows: H20 + CO2 --H2CO3.

Thus a weakly acidic groundwater moves through the networks of joints, fractures and faults in the dolomite. This weak acid acts on the dolomite resulting in the rock going into solution in the form of bicarbonates.

3CaC032MgC03	+	5H2C03	=	3Ca(HC03)2	+	2Mg (HC03)2
Dolomite		Carbonic Acid		Calcium Bicarbonate		Magnesium Bicarbonate

The weathering of the rock has given rise to cave systems, voids and other solution features, which make it a unique rock on the South African landscape. Other rock types do not display this degree of solubility and are consequently not as prone to cavitation. Materials can either collapse or be transported into these voids and cave systems resulting in surface ground movement; sometimes with catastrophic results. The manifestation of this ground movement on the surface is either as a sinkhole or a doline.

2.3 Stratigraphy of the dolomite.

The dolomite of the Transvaal is stratigraphically represented in the Chuniespoort Group.

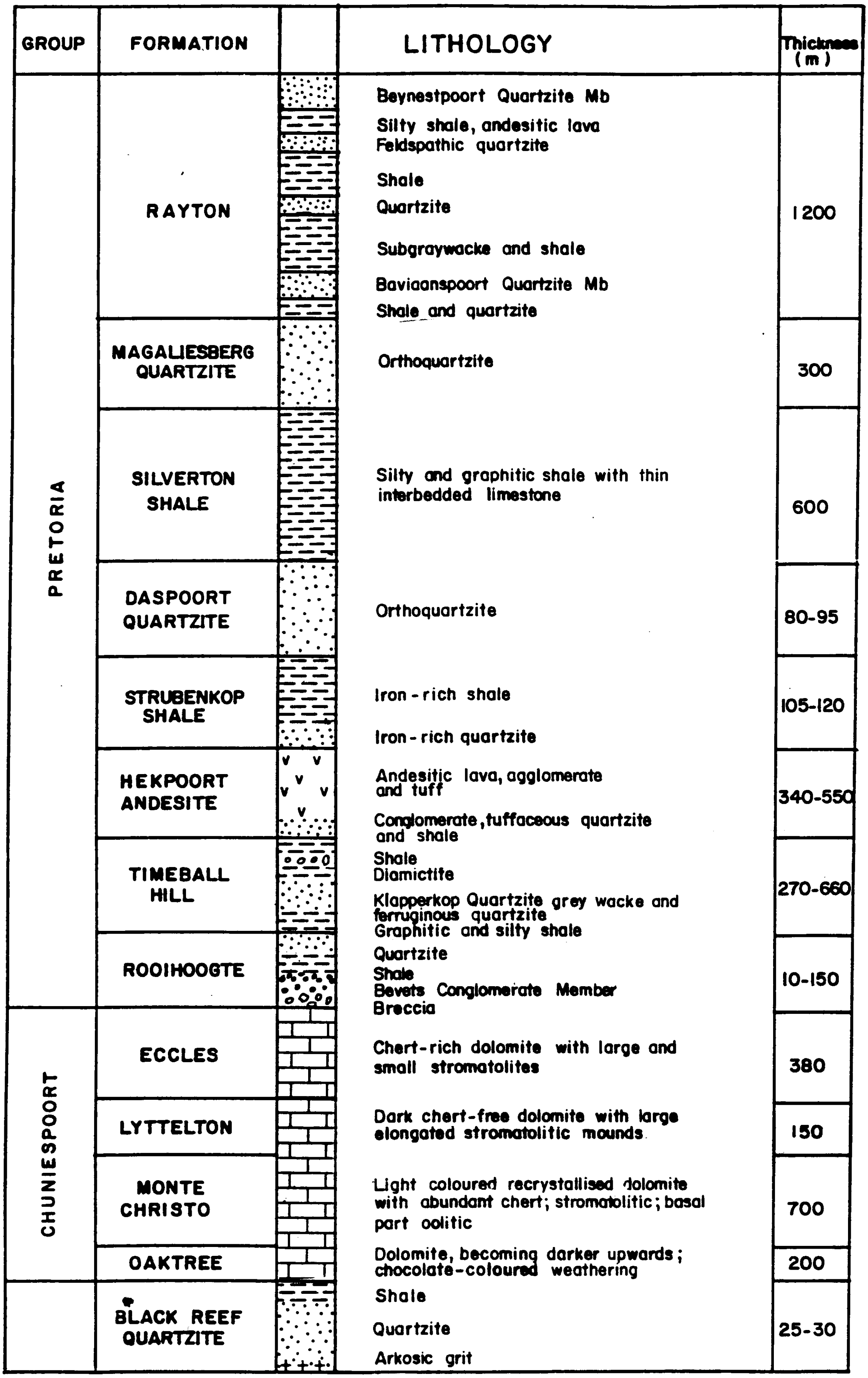
2.3.1 Chuniespoort Group.

The dolomite rocks of the Chuniespoort Group are about 2200 to 2300 Ma years old and occupy an area of approximately 15 000 square kilometres or 5 percent of the surface area in the Transvaal. Van Schalkwyk (1981) estimates that these outcropping rocks constitute about twenty percent of the surface area of the Pretoria / Witwatersrand /Vereeniging Complex.

The Chuniespoort Group consists of four formations in the PWV area, namely the Oaktree, Monte Christo, Lyttelton and Eccles Formations (Figure 2). The Frisco Formation is absent in the Pretoria - Witwatersrand - Vereeniging area and the Pretoria Group sediments rest unconformably on the dolomite of the Eccles Formation. The Frisco Formation is however represented in the Western and Eastern Transvaal (Figure 3 and 4).

The four formations represented in the PWV area are collectively approximately 1430 metres thick and are identified on the basis of the relative abundance of interbedded chert (Si02). The Oaktree and the Lyttelton Formations are chert poor, while the Eccles and Monte Christo Formations are rich in chert.

CENTRAL TRANSVAAL



GROUP	FORMATION	LITHOLOGY	Thickness (m)
PRETORIA	RAYTON	Beynestpoort Quartzite Mb Silty shale, andesitic lava Feldspathic quartzite Shale Quartzite Subgraywacke and shale Baviaanspoort Quartzite Mb Shale and quartzite	1200
	MAGALIESBERG QUARTZITE	Orthoquartzite	300
	SILVERTON SHALE	Silty and graphitic shale with thin interbedded limestone	600
	DASPOORT QUARTZITE	Orthoquartzite	80-95
	STRUBENKOP SHALE	Iron-rich shale Iron-rich quartzite	105-120
	HEKPOORT ANDESITE	Andesitic lava, agglomerate and tuff Conglomerate, tuffaceous quartzite and shale	340-550
	TIMEBALL HILL	Shale Diamictite Klapperkop Quartzite grey wacke and ferruginous quartzite Graphitic and silty shale	270-660
	ROOIHOOGTE	Quartzite Shale Bevets Conglomerate Member Breccia	10-150
CHUNIESPOORT	ECCLES	Chert-rich dolomite with large and small stromatolites	380
	LYTTELTON	Dark chert-free dolomite with large elongated stromatolitic mounds	150
	MONTE CHRISTO	Light coloured recrystallised dolomite with abundant chert; stromatolitic; basal part oolitic	700
	OAKTREE	Dolomite, becoming darker upwards; chocolate-coloured weathering	200
	BLACK REEF QUARTZITE	Shale Quartzite Arkosic grit	25-30

Figure 2: Chuniespoort and Pretoria Groups in the central area of the Transvaal (After SACS 1980).

Figure 3 : Distribution of the Chuniespoort and Campbell Groups.

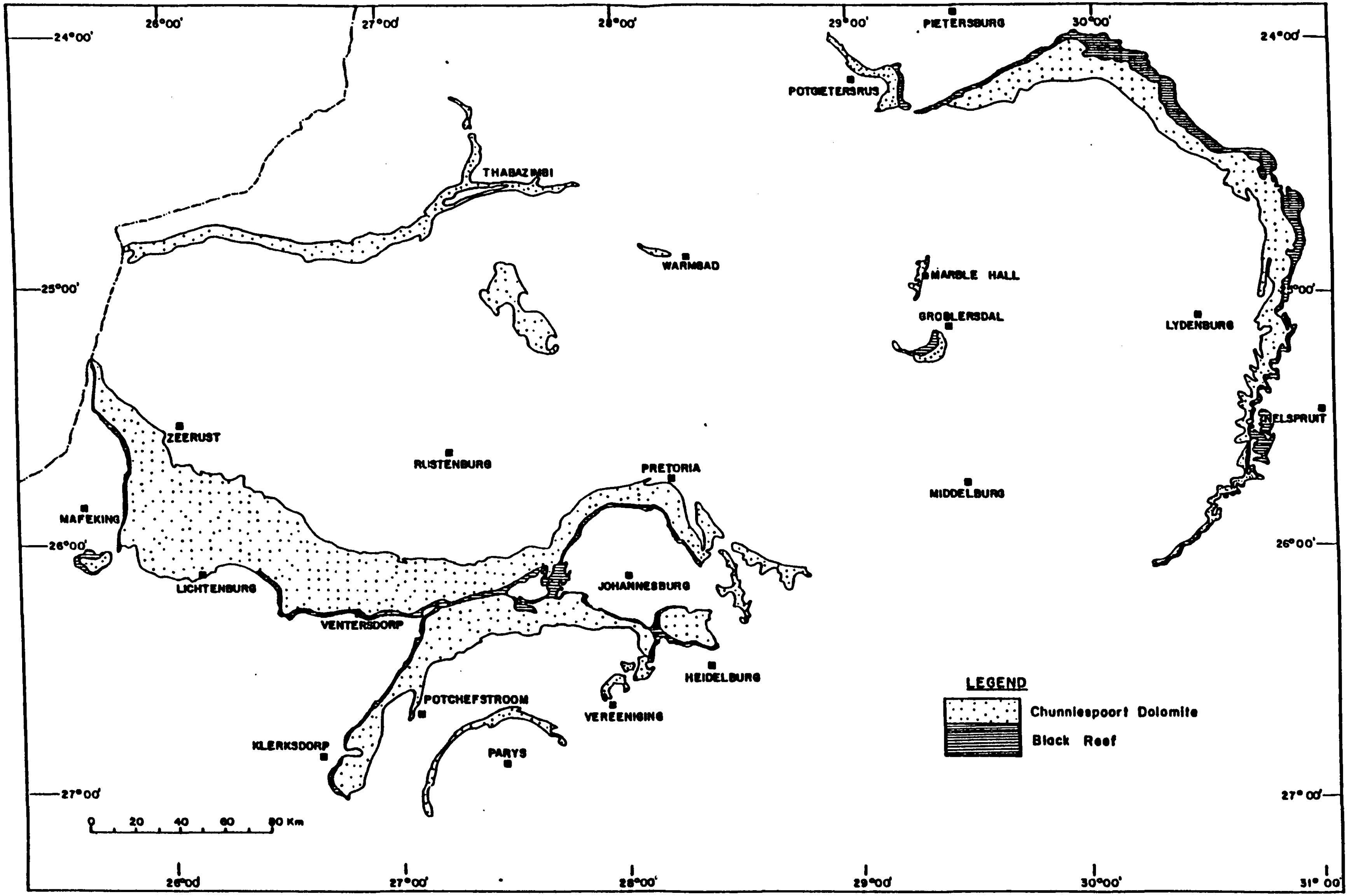


Figure 4: Distribution of the Chuniespoort Group in the Transvaal.

2.3.2 Black Reef Quartzite Formation.

The Black Reef Quartzite Formation which underlies the Chuniespoort Group rocks, is approximately 30 metres thick and consists of shale, quartzite, dolomite and conglomerate.

2.3.3 Frisco Formation.

The dolomite of the Frisco Formation is not present in the central area of the country.

2.3.4 Eccles Formation.

The dolomite of the Eccles Formation is rich in chert with the chert content increasing upward in the succession. This formation is approximately 400 metres thick.

2.3.5 Lyttelton Formation.

The Lyttelton Formation, which is 150 metres thick, consists of dark, chert free dolomite, with large elongated stromatolitic mounds (SACS, 1980). The width of the structures may range from less than five to over 30 metres (Eriksson and Truswell, 1974). The dolomite tends to weather into sharp pinnacles. ✓

2.3.6 Monte Christo Formation.

The Monte Christo Formation, which is in excess of 700 metres thick, is usually the most thickly developed formation. The formation is chert rich and displays stromatolites in recrystallised dolomite. The basal zone is oolitic. These strata rest concordantly on the rocks of the Oaktree Formation.

2.3.7 Oaktree Formation.

The Oaktree Formation is approximately two hundred metres thick, consisting of dark coloured, chert-poor dolomite with some carbonaceous shale towards the base (SACS 1980). This formation constitutes the basal unit of the Chuniespoort Group.

2.3.8 Syenite/Diabase Dykes and Sills.

Innumerable syenite/diabase sills and dykes have intruded the Chuniespoort Group.

2.4 The Environment of Deposition.

The early Proterozoic Transvaal and Griqualand Sequences accumulated in a 500 000km2 intracratonic epeiric basin on the Kaapvaal crustal fragment. This enormous basin was developed during a major period of erosion in Post-Ventersdorp times. The Black Reef quartzite covers a regional unconformity overstepping the basement granites and the Ventersdorp volcanics. The northeast, southwesterly orientated basin contains a substantial thickness of Chuniespoort chemical sediments.

Both fluvial and shallow marine facies are discernable in the Black Reef strata (Button 1973). The Black Reef quartzite fines upwards into interbedded shale before grading into the overlying Chuniespoort Group.

2.5 Sinkholes and Subsidences.

2.5.1 Sinkholes.

A sinkhole results from the hollowing out of a space below the surface of the earth which eventually breaks through to the surface. Usually it is a cylindrical to conical hole of 3-50 m diameter and 1-50 m deep.

Sinkholes:

- are unpredictable, as they can occur anywhere in dolomite land.
- can be catastrophic, as they occur unexpectedly with little or no warning.
- can cause property damage or loss of life, if they are sufficiently large.
- are usually precipitated by human activity such as dewatering, due to mining activity, water extraction from aquifers, leakage of wet services such as water supply and sewer bulk services, reticulation and connections interference with natural drainage patterns by development and disturbance of superficial soil materials leading to concentrated water ingress.

It is important to note that the lateral extent and effects of dewatering are difficult to control or predict, because dewatering activities in areas controlled by one authority may effect aquifers under land controlled by another authority.

2.5.1.1 The classical mechanisms of sinkhole formation.

Jennings et al., (1965) noted that there is considerable evidence to show that a sinkhole occurs by the collapse of an arch spanning an air-filled void (Figure 5).

The arch is seen to lie wholly within the residuum above the dolomite bedrock interface. The collapse of the arch occurs by onion peeling with the ravelling material falling to the floor of the void. In this manner the void migrates to the surface, manifesting itself as a sinkhole.

Jennings et al.,(1965) noted that a number of interdependent conditions are required for a sinkhole to form namely:

1. There must be adjacent rigid material to form abutments for the roof of the void. These are provided by the dolomite pinnacles or sides of the steep-sided subsurface canyons as illustrated in Figure 5. The span must be appropriate to the strength of the bridging material since, with a span which is too large, the arch cannot form.

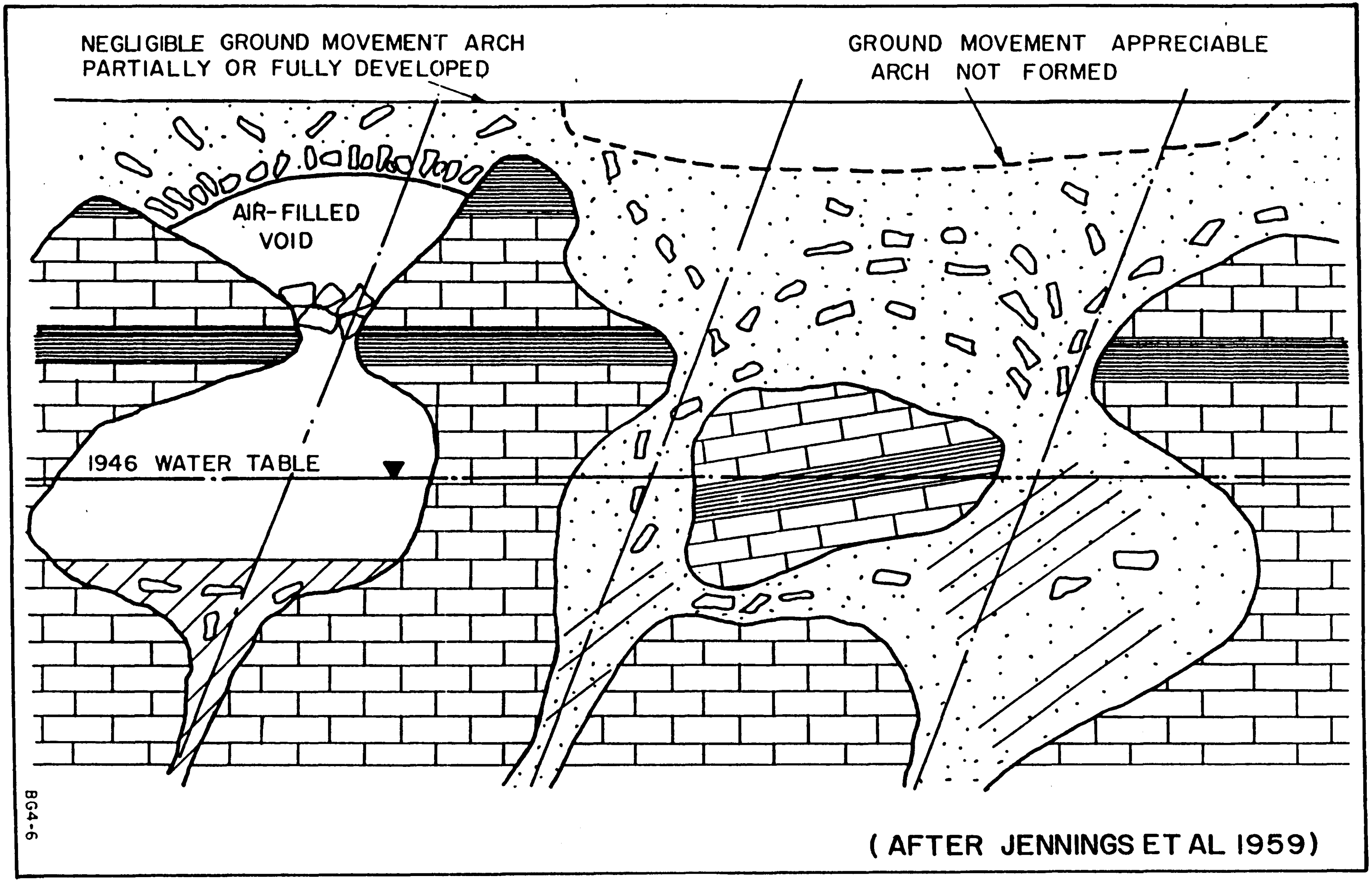


Figure 5: Sinkhole and doline formation.

2. A condition of arching must develop in the residuum, i.e a portion or all of the vertically acting selfweight must be carried by arching thrusts to the abutments. Complete arching will have occurred when the vertical stress along the intrados is zero.

3. A void must develop below the arch in the residuum. This void may be small, for example, a horizontal crack which may not be disclosed by drilling.

4. A reservoir must exist below the arch to accept the material which is removed to enlarge the void described in (3) above, to substantial size. Some means of transportation for the material, such as flowing water, is also essential.

5. When a void of appropriate size has been established in the residuum, some disturbing agency must arise to cause the roof to collapse. The void will move progressively upwards towards the surface. A common agency causing collapse is water in the arched material which leads to loss of strength or washing out of critical binding or keying material. This process is the trigger which initiates the collapse of the arch leading ultimately to the sinkhole.

Jennings et al., (1965) further noted that these five conditions must occur successively and if any one is absent, the sinkhole will not form. For example, if the span is too large in relation to the strength of the residuum material, any removal of material, will be accompanied by surface settlement. This condition will lead to caving subsidence. There is also nothing to prevent caving subsidence proceeding until blockage results at the point of subsurface draw-off. The surface movement will then slow down, and separation, forming a void, will occur below the point of blockage. Similarly, if there is no mechanism for transportation or deep consolidation, the enlarged void cannot develop and the sinkhole will not form. Caves only contribute indirectly to the process of sinkhole formation by providing the reservoir for the removed material. Jennings et al (1965) claim that in general, sinkholes do not form by collapse into such caves.

2.5.1.2 Other mechanisms of sinkhole formation.

Buttrick (1987) reviews the role of wad and other materials in stability evaluation and touches on some other naturally and artificially induced processes which may give rise to sinkhole formation. Ingress water may, by a process of internal erosion, lead to the creation of a void or several voids which eventually collapse. This process would deviate from the order of events stated by Jenning et al, in which it is envisaged that the ingress water would be the final contributory factor. The nature of the material constituting the blanketing layer is crucial in determining the mechanism by which sinkholes are developed due to ingress water (Figure 6).

If the blanketing layer is composed of a highly permeable material the percolating water is able to achieve the critical flow velocity required to overcome the hydrodynamic stability of the particles. Consequently erosion results. Materials in the blanketing layer reflecting this susceptibility include:

1. Gap graded materials such as chert rubble and fines. A multitude of potential flow paths exists in these materials. The interfaces between chert boulders and fragments and the surrounding fines matrix represent potential flow paths.

2. Open, intensely fissured soils such as silty clays (wad) will present multitudes of potential flow paths.

The percolating water exploits the flow paths, "plucking" soil particles from the walls of these routes. The water carries fines down into the lower lying reaches of the profile and into a receptacle or disseminated receptacles.

The nature of the upper profile material determines whether arching takes place with a final catastrophic collapse or if there is gradual settlement with final collapse. In the case of the former, the presence of a competent layer (e.g. a ferruginised layer) will encourage arch formation.

If the blanketing layer is composed of material of low permeability (e.g. clayey silt, silty clay (wad), ferroan soils etc.) ingress water is unable to percolate rapidly enough, to affect erosive activity. A plume of moisture develops around the lower part of the leaking service and gradually migrates downwards. At the soil/air interface above the receptacles, water from the plume exits, initially as a trickle. As the water gains in volume and velocity, soil particle "plucking" is initiated and the process of headward erosion

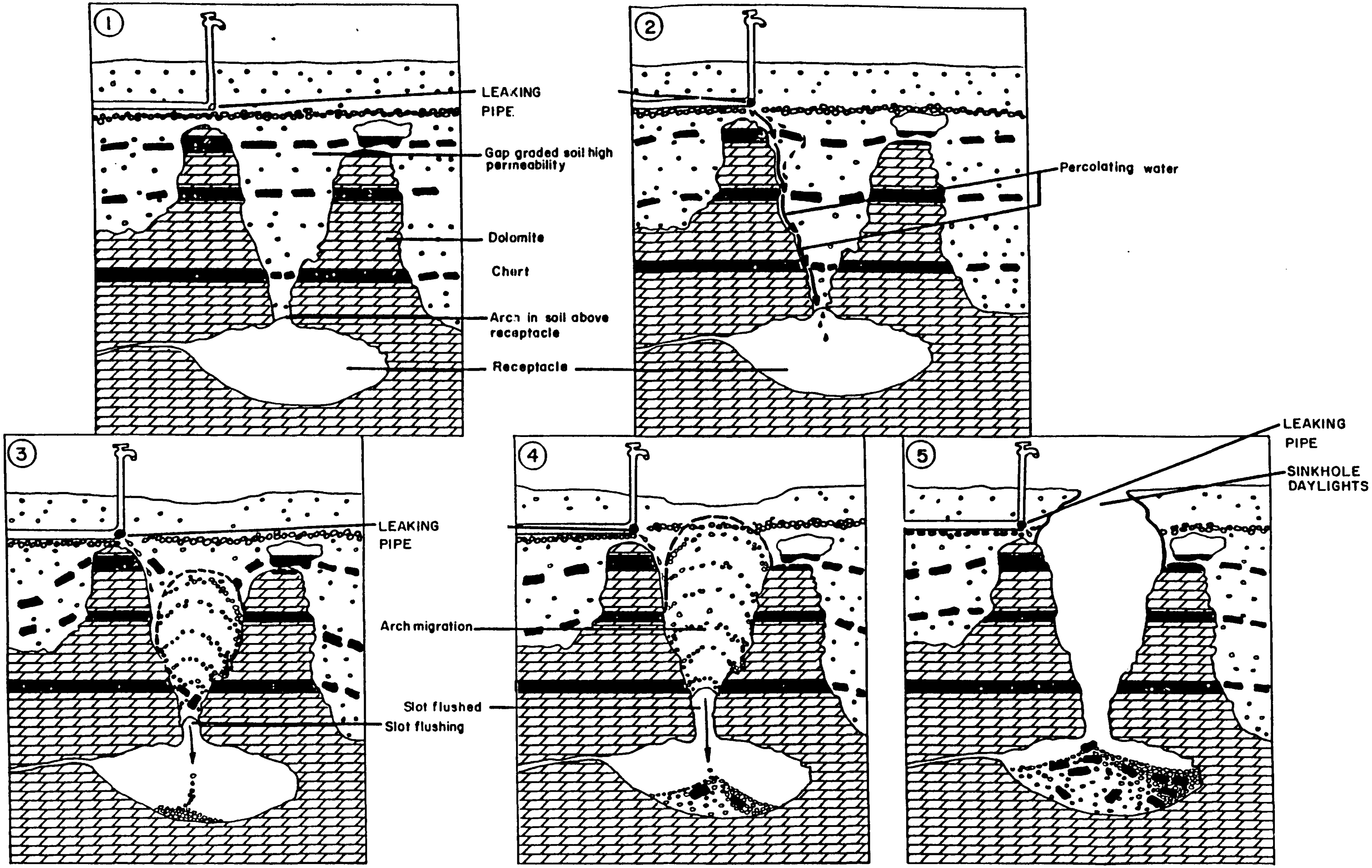


Figure 6: A mechanism of sinkhole formation involving subsurface erosion.

begins. This piping erosion process results in increasing amounts of soil material being transported into the receptacle. The result is that a void develops and migrates towards the surface (Figure 7).

2.5.2 Dolines.

A doline is an area of subsidence which develops as a result of the consolidation or displacement of underground material, reducing support to the extent that the surface layers subside. *The term doline is now used by engineering geologists to refer to the manifested geomorphological feature and not to the formation process.*

Dolines:

- are less sharply defined than sinkholes and
- occur slowly and not catastrophically
- can be on a very large scale (kilometres in length, although the more typical size range is 50-300 m long and about 1 m deep. Dolines of this size are usually associated with large-scale dewatering due to mining activity).
- structures may be damaged.
- are sometimes arrested by natural processes (choking) or the cessation of water penetration from leaking services.

Water penetration in the shear zone around the perimeter of a doline, could lead to sinkhole formation.

2.5.2.1 Mechanisms of doline formation.

The dolomitic karst environment is often characterised by zones of deep weathering and preferential leaching. This process of preferential weathering is particularly well advanced within the shear zones of faults. Subsurface karst valleys up to 200 m in depth may develop in these shear zones. Spectacular representations of these features can be seen on the residual gravity survey of the Far West Rand area, along fault zones (Figure 8). Leaching of the dolomite resulting in these features has been active for long periods of geological time. As the weathering progresses, the surface subsides to form elongated and enclosed depressions or

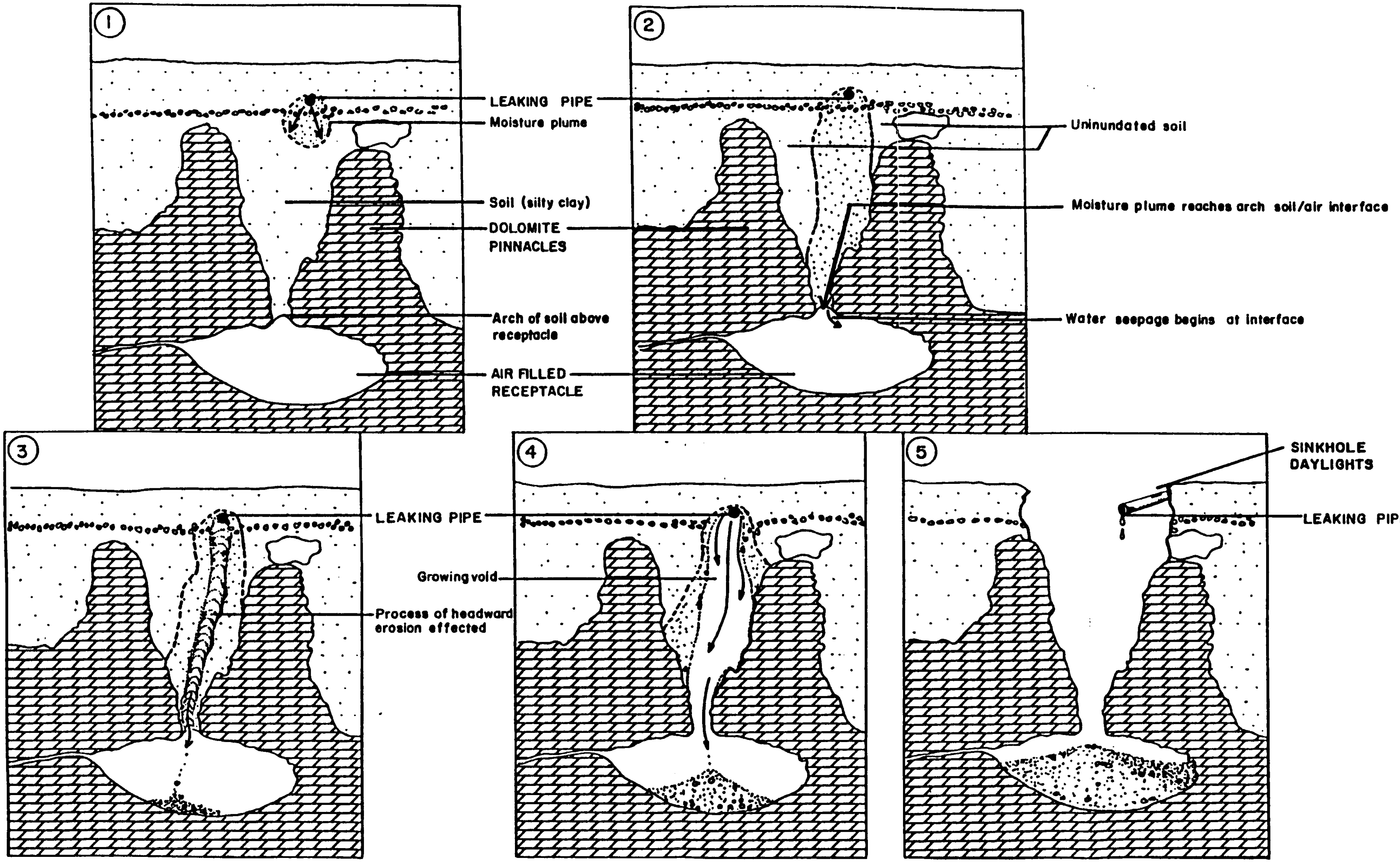
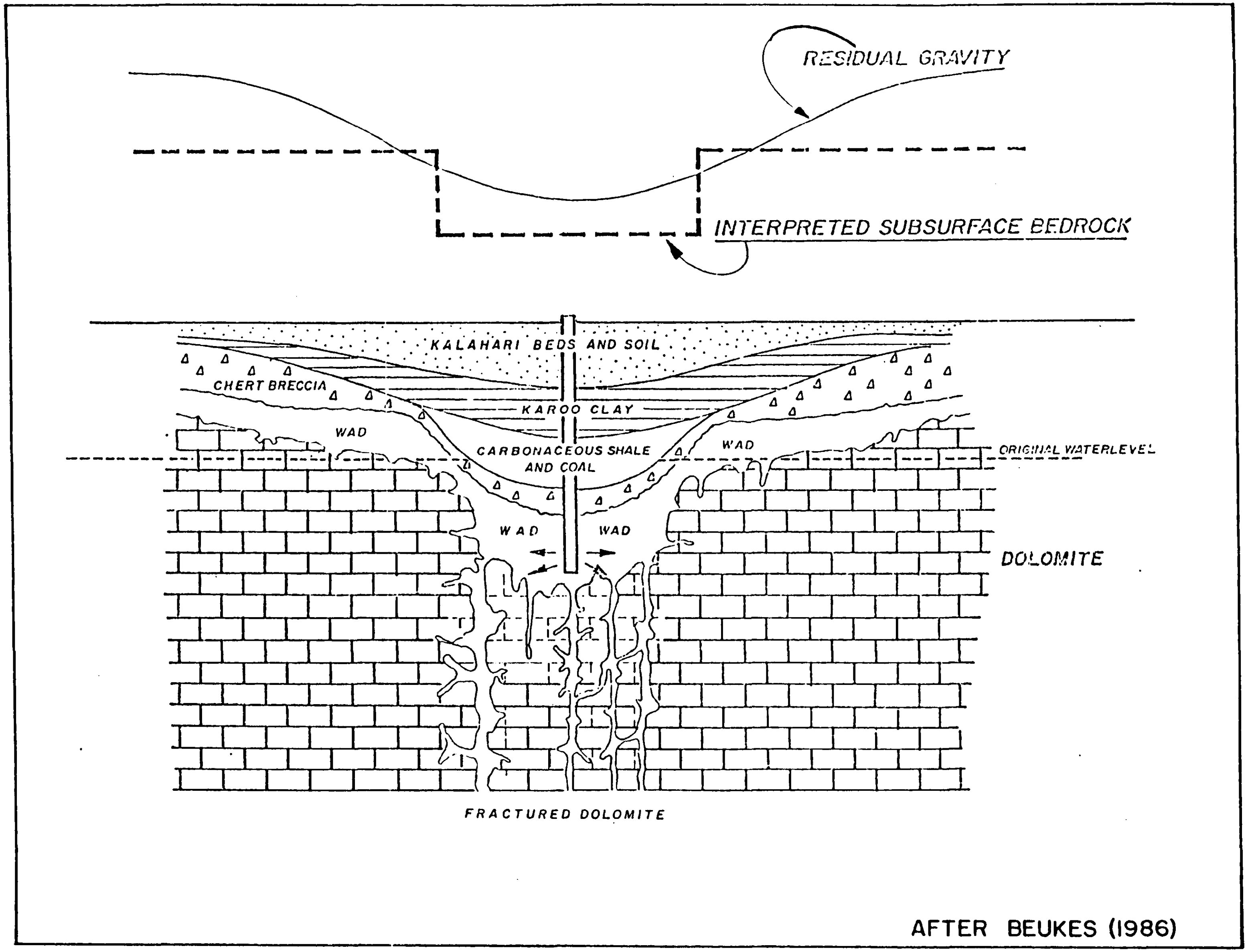


Figure 7: A mechanism of sinkhole formation involving piping erosion.



AFTER BEUKES (1986)

Figure 8: Schematic representation of a deeply-leached zone in the dolomite reflecting a potential for sinkhole formation.

natural dolines. These depressions may subsequently have been filled with Karoo materials, hillwash or aeolian sands.

There are large expanses of dolomite which have been subjected to more uniform weathering laterally, resulting in a gentle undulating dolomite interface with substantial residual soil cover. The residual soil component of the subsurface profile may be of the order of fifteen to twenty metres in thickness.

In many of these areas, the watertable is located above the bedrock interface and it is presently located in the residual soils. These residual materials are essentially composed of wad and ferroan soil. The artificial lowering of the water table may produce significant ground movement at surface (Figure 8). Brink (1979) explains that "the lowering of the water table is roughly equivalent to placing a surcharge load at an elevation halfway between the initial and final water table levels; the loading being that which would be exerted by a head of water equivalent to the drop in the water table. Thus if the water table were lowered by 100 m, the effect would be the same as placing a load of 100 x 9,81= 981 kPa at the mean elevation of the old and the new levels of the water table. As the water in the voids of the soil below the original water level drains out, settlement occurs as denoted by Terzaghi's consolidation theory". The magnitude of the settlement is dependent on the compression index (Cc) of the consolidating material and the rate of settlement on the coefficient of consolidation (Cv).

The potential for dramatic ground settlement is reflected in the geotechnical properties of the residual dolomitic soils such as wad and ferroan soils. Buttrick (1986) notes that wad and ferroan soils may be characterised by dry densities as low as 220 kg/m3 while Roux (1984) notes values as low as 80 kg/m3. The extremely low values indicate the very porous nature of the material. The average void ratio's for these soils are in the vicinity of 5 with the highest recorded value being 16,6. Buttrick (1986) indicates that the compression index values may be as high as 6,7. These values indicate a high compressibility when one considers that most clays have a compression index of less than 0,5. Experience, gained particularly in chert-rich formations south of Pretoria, indicates that doline formation may also be induced by ingress water. If the sub-surface profile is composed of a highly permeable material, the percolating water is able to achieve the critical flow velocity required to overcome the hydrodynamic stability of the particles. Consequently erosion is initiated.

Materials in the blanketing layer reflecting this susceptibility include:

1) Gap graded materials such as chert rubble and fines. A multitude of potential flow paths exists in these materials. The interfaces between chert boulders, fragments and the surrounding fine matrix represent potential flow paths.

2) Open,intensely fissured soils such as silty clays (wad) present multitudes of potential flow paths. The percolating water exploits the flow paths, "plucking" soil particles from the walls of these routes. The water carries fines down into the lower reaches of the profile and into a receptacle or disseminated receptacles. If the coarse component of the soil dominates, the rubble will merely fall into a denser state of packing as the fines are removed. The result is that movement will manifest itself at the surface with the formation of an enclosed depression or doline. Alternatively, in a profile where the fines are dominant, the downward transportation of material may cease if the disseminated receptacles are either choked or the mobilising agency is removed. The process of sinkhole formation would be therefore be terminated prematurely with the manifestation being only a surface depression.

2.6 Consequences of development on dolomite.

Whenever urban development occurs on dolomite, man may be exposed to the potentially negative consequences and side effects of his activities if appropriate precautionary measures are not taken. Activities associated with development normally result in a disturbance of the metastable conditions previously prevalent in the dolomite karst environment. Natural drainage patterns are artificially altered, water concentration is induced, natural flow velocities may either be enhanced or retarded, superficial soil materials disturbed and their permeabilities negatively influenced, waterbearing services concentrate "foreign" water in the subsurfaces profile and the geohydrology may be dramatically altered.

The causes of 101 sinkholes in a small study area south of Pretoria were analysed by Roux (1984). It was found that all these sinkholes were artificially induced as a consequence of man's activities. No natural sinkholes were recorded. In a more recent study by Schoning (1990) it has been found that over 96 per cent of a total of 380 sinkholes and subsidences, recorded on the dolomites in an essentially middle class area south of Pretoria, were induced artificially.

The degree of risk related to housing development on dolomite may be assessed by statistical analyses and experience. Van Schalkwyk (1981) indicates that, with some exceptions, the risk of both property damage and loss of life due to sinkhole formation is 2 to 20 million times less than that due to lightning. Lightning is normally regarded as one of the negligible hazards in normal life. Consequently many town planners, developers, local authorities and provincial officials have formulated the opinion that stability investigations, remedial and precautionary measures are unnecessary prerequisites. These protagonists believe that the potential for loss of life and damage to property have been exaggerated and that unnecessary costs are being incurred. False security may be derived from this comparison with lightning statistics. Precautionary measures have been applied for at least 24 years in certain dolomite areas, particularly more costly, low density development with a low density of waterbearing services. These factors have assisted in reducing the risk of sinkhole formation. However, the emphasis now is on high density, low cost development with a population density of up to 2 000 per cent greater than that in the existing middle class developments.

Common population densities in the "low density" areas average 60 persons per hectare, whereas the figure for high density areas may reach 720 persons per hectare. In addition, Van Schalkwyk's (1981) cited statistics constitute an average figure, based on 6 geographical areas with markedly differing dolomitic risk characterisations. As an example, the community of Rooihuiskraal has experienced neither incidences of ground movement nor loss of life due to sinkhole formation. Alternatively the community of Venterspost has experienced the loss of 1 life and 1 in 3 properties have been evacuated due to ground movement.

The aspects of loss of life and financial implications of inappropriate development on dolomite will briefly be discussed.

2.6.1 Loss of life.

The spectacular and tragic consequences of man's activities in the dolomite environment were mirrored in the news headlines of the early sixties.

A total of thirty eight people were interred in sinkholes

(Table 3 and Plates 1 and 2). It is events such as these that have underscored the need for careful evaluation of the stability of sites prior to development.

2.6.2 Financial implications of inappropriate development on dolomite.

2.6.2.1 Far West Rand.

The Far West Rand experience provides an ideal opportunity for back analyses and review of the financial implications of events in an environment where stability investigations were originally not conducted and where man's activities disturbed the metastable environmental state.

To convey the enormity of the financial implications of these events, valuable information has been extracted from the annual reports of the Chairman of the Far West Rand Dolomite Water Association (FWRDA). This association was voluntarily formed by its first members (Blyvooruitzicht, Libanon, Venterspost, West Driefontein and Western Deep Levels Gold Mining Companies) on the 6 July 1964. The objectives of this association are to:

i) ensure that the dewatering of certain ground water compartments is not impeded by activities on land either within or adjacent to such compartments by persons/bodies controlling the flow of water therein.

ii) To undertake measures to promote safety in compartments subject to dewatering.

iii) To receive, investigate, consider, settle or dispose of all claims made against its members in respect of damage alleged to have been caused to claimants by dewatering.

The financial data utilised in the following pages includes figures pertaining to such matters as compensation, remedial work to secure affected ground and maintenance of vacated ground in developed areas of the Far West Rand (Table 4). The principle mobilising agency in this area has been rapid artificial drawdown of the

INCIDENT	DATE	LIVES LOST	SINKHOLE DIAMETER (m)
West Driefontein	12/12/1962	29	> 55m
Blyvooruitsig	03/08/1964	5	> 55m
Verwoerdburg	1970	3	5m
Venterspost	24/10/1970	1	> 5m

Table 3: Loss of life in sinkholes

Plate 1: Blyvooruitzicht Sinkhole, 3 August 1964 -
Five lives lost.

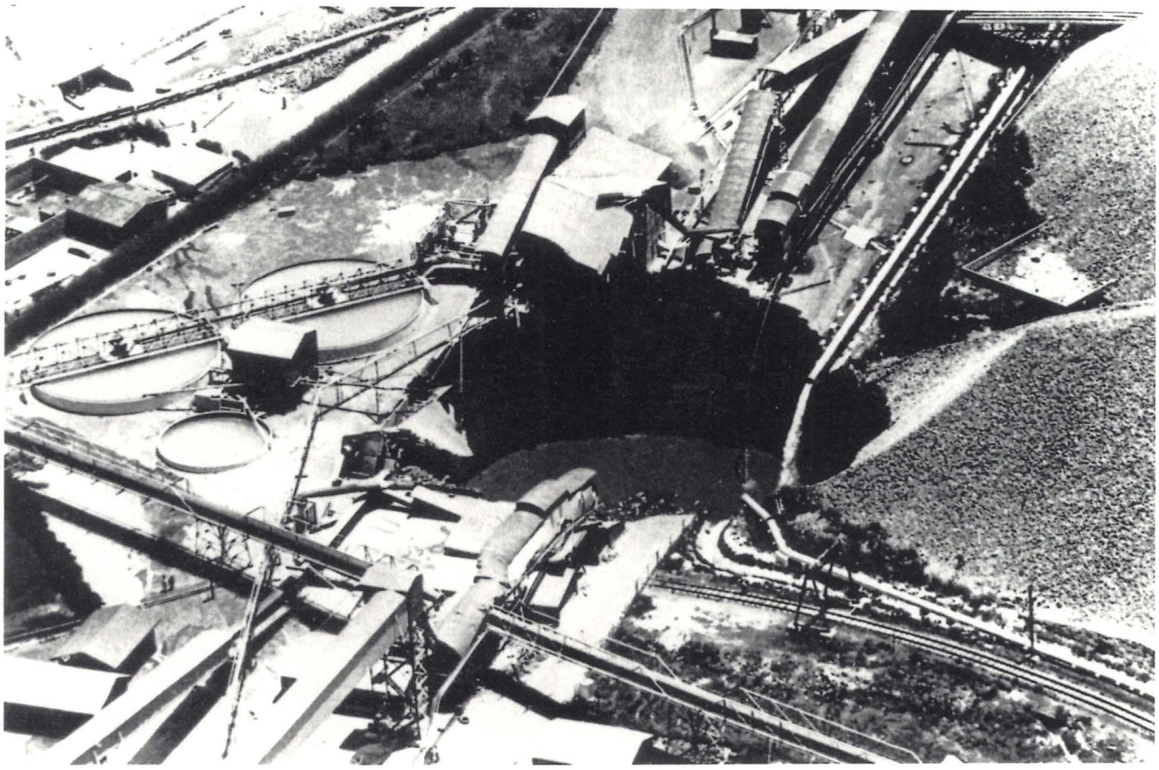


Plate 2: Sinkhole: Crusher Plant - west Driefontein Gold Mine, 12 December 1962 - Twenty nine lives lost.

Plate 3: Ablution block in complex south of Pretoria suffering severe structural distress.

TABLE 4

FAR WEST RAND DOLOMITIC WATER ASSOCIATION

PROPERTIES REGISTERED IN THE NAME OF THE ASSOCIATION

AS AT 30 JUNE 1987

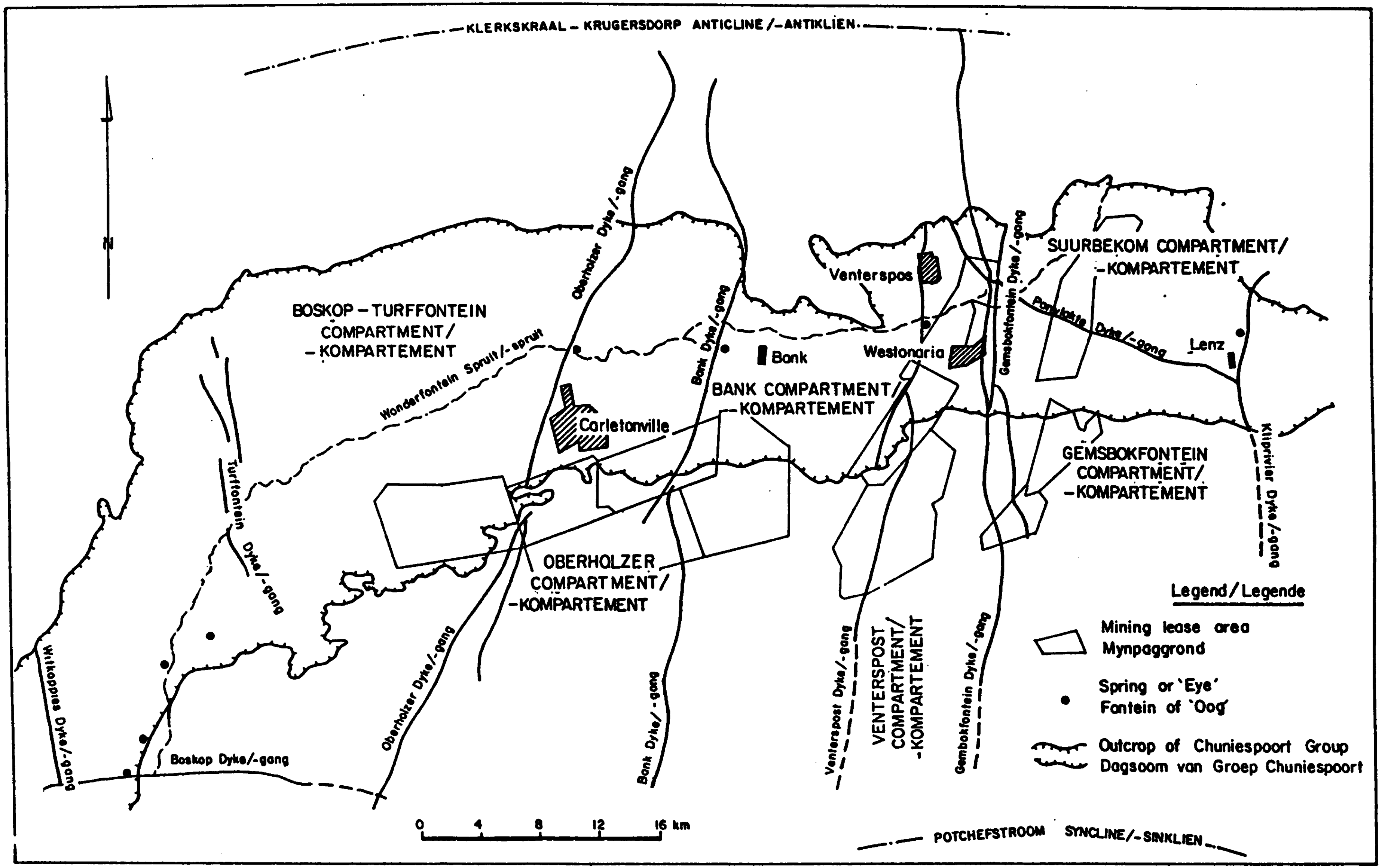
COMPARTMENT	FARMS AND AGRICULTURAL HOLDINGS	TOWNSHIP STANDS		OTHER EXPENDITURE (ADMINISTRATION, DRILLING, COMPENSATION, ETC.)
		IMPROVED	UNIMPROVED	
TURFFONTEIN	9 836,610 3 ha	-	-	R 4 320 600
OBERHOLZER	4 727,856 3 ha	25	47	
BANK	9 649,644 8 ha	50	1 417	10 926 941
VENTERSPOST	476,700 7 ha	13	5	4 475 102
GEMSBOKFONTEIN	499,918 0 ha	9	-	19 976 026
TOTALS:	25 190,730 1 ha	97	1 469	39 698 669

watertable resulting in large scale ground movement (Plates 1, 2 and 3). The affected groundwater compartments are Turffontein, Oberholzer, Bank, Venterspost and Gemsbokfontein. The largest communities established in these areas are Carletonville, Westonaria and Venterspost (Figure 9).

Since the formation of the FWRDA in 1964, 25 665 hectares of land have been purchased (Table 4). Purchasing this land effectively followed classification of the property as "problematical". Many of the portions purchased may not have actually been damaged but were either purchased in terms of an agreement with the State or because uneconomic units would have remained when damaged portions were purchased. The value of original improvements on the land purchased exceed R21 million, but most of these improvements have been demolished over the years, including virtually all the improvements on land in the Bank and Venterspost Compartments (FWRDA Annual Report 1987). In addition, 2138 township stands have been purchased since inception of the FWRDA having been determined as either unsuitable for development or unsafe for continued occupation.

Examination of the annual report for 1986/1987, reveals that 63 claims for compensation were settled during that year at a cost of R8 639 502. These claims related to property within existing communities, damaged or determined as unsuitable for occupation or development. A further example of the financial implications associated with induced instability events, is derived from the 1985/1986 Chairman's report of the Far West Rand Dolomite Water Association. During that year a total of 84 claims for compensation were finalised at a cost of R8 166 500 (Table 5).

Table 5 denotes the sum of money spent on various items selected from the reports of the Far West Rand Dolomite Water Association for the period 1980 to 1987. Large sums of money were spent on items such as road repair and reconstruction. This period has been selected as it reflects the expenditure patterns of a recent time interval. Consequently these figures cited still bear some relevance in terms of relative financial value. During the period under review, R1 056 292 was spent on compensation for damaged property, R1 383 126 in fixed assets was written off and R84 143 was spent on the process of demolishing structures declared unsafe for occupation. A staggering amount of R20 370 942 was spent on drilling boreholes to determine stability conditions, filling sinkholes, repairing and maintaining structures and roads and on



(AFTER ENSLIN ET AL.1976)

Figure 9: Far West Rand dolomitic area.

TABLE 5 : EXPENDITURE ON SELECTED ITEMS BY FWRDA 1980 - 1987

Expenditure	1980	1981	1982	1983	1984	1985	1986	1987	Total
Compensation	100381	201108	186604	179787	52993	17432	1412	316575	1056292
Demolish Buildings	6300	53427	19916	-	-	-	1100	3400	84143
Drilling	4328	6298	13012	31312	64747	204440	462320	828303	1614760
Filling of Sinkholes	2123	11596	2760	1900	20061	10713	22431	191271	262855
Fixed assets written off.	-	-	-	-	126127	1099738	22921	134340	1383126
Geological Costs	20693	27302	39656	47421	69672	13371	18642	31205	267962
Property inspection	-	-	10125	10150	10225	13650	9675	11300	65125
Rates & Taxes	54510	37317	44630	59062	48398	56398	68651	82467	451433
Repairs & mt.	24885	30966	33064	28014	67002	114913	119889	87183	505916
Road Repairs &	89524	-	132	256377	301449	42764	7086310	469778	8246334
Professional sevices w.r.t.Gemsbokfontein reconstruction	-	-	-	-	-	-	5752615	5251117	11003732

the procurement of the related, professional services. The road P89/1 from Randfontein to Carletonville via Bank was severely damaged due to ground movement and has been closed since 1970. In the 1983 financial year the FWRDA made an ex-gratia payment of R2,2 million towards the costs of reconstruction.

In the annual report of the Association dated 30 June 1986 an expenditure of R20 876 059 was noted for a single ground water compartment.

This expenditure was constituted as follows:

Land Purchases	R8 049 755
Other Expenses	R 129 826
Professional Services	R5 752 615
Road repair and Maintenance	R6 878 973
Valuations	R 64 890

In the following years, further large sums of money have been spent.

The Annual Report of the Association for 1988 indicates that 10 claims were finalised at a cost of R1 653 859, 2 142 township stands had been purchased since inception of the FWRDWA and a total expenditure of R7 397 768 on compensation, drilling costs and so on (FWRDWA Annual Report 1988).

In townships, such as Venterspost, cognizance was not taken of the dolomite issue prior to the original positioning of the communities. At that stage, the density of development was lower and man's influence on the dolomitic karst environment was limited. These townships had been located, designed and developed prior to dewatering of the dolomitic aquifers. The subsequent disturbance of the environment had a devastating effect on the well-being of the populace and has had costly financial implications.

Venterspost was originally a township of 1887 stands. By May 1981, 525 of the stands had been declared unsuitable for development or continued occupation. Continued occupation of many other portions of the township was permitted only because the development was already present. The loss of a third of the community has obviously affected the viability of the development. There are problems of aesthetics, losses in revenue from now vacant land, keeping properties free of vermin, etc. Obviously property values in the area have plunged.

Table 4 depicts the assets of FWRDWA in the various ground water compartments. The interesting factor is the extent to which expenditure on securing the meta-stability of the land exceeds the value of the assets. This expenditure includes the costs of drilling, administration, compensation and maintenance.

2.6.2.2 Other Dolomite Areas

Further examples of the effects of having inappropriate development in relation to risk can be derived from other dolomite karst areas where different mobilising agencies may dominate. As previously stated, a total of some 380 sinkholes and subsidences have been recorded in the dolomite karst area south of Pretoria, predominantly in areas not previously investigated. The principle mobilising agency for these events was ingress water. Only three people lost their lives in these events. The effects of these events, however, on the well-being of the populace and the financial consequences must be noted. Incidents such as these touch the confidence of the populace of an affected area, triggering a sequence of disconcerting events including, newspaper and other media reports, rumours, loss of confidence in an area and uncertainty amongst the institutions providing bonds and insurance cover.

Changuion (1981) indicates that of the 117 stability investigations conducted in the military complex of Verwoerdburg during a five year period ending in 1981, 35 per cent of the investigations were conducted on existing structures. These investigations were related to remedial work geared to repair structures damaged due to sinkhole /subsidence formation (Table 6 and Plate 4). During the same period 31 per cent of the investigations conducted, in a high density complex just south of Irene, were related to existing structures damaged due to ground movement. In Voortrekkerhoogte the figure is 32 per cent (Table 6).

Changuion (1981) notes that several stability problems are reported in the military complex weekly. These reports are investigated by the departments of Public Works and the Geological Survey. As an example, during the period of one month in mid 1987, the Unit for Applied Studies on Dolomite at the Geological Survey, inspected forty sites and structures suffering structural damage. All these sites are within a small area of intensive development on the dolomite south of Pretoria.

REGION	TOTAL NUMBER OF INVESTIGATIONS	INVESTIGATIONS OF EXISTING DEVELOPMENTS
Johannesburg: Lenasia	20	0
Kuruman	1	0
Lichtenburg	2	0
East & West Rand	5	1
Olifantsfontein	1	0
Postmasburg	1	1
Potchefstroom	5	0
Pretoria: Attridgeville, Claudius, Laudium	5	0
Pretoria: Voortrekkerhoogte	72	23 (32%) x
Sishen	3	0
Stilfontein	1	0
Verwoerdburg: Irene	13	4 (31%) x
Verwoerdburg:Military Area	117	41 (35%) x

Table 6 - Investigations on dolomite (after Changuion 1981).

Plate 4: Structural damage due to ground settlement

The structures are all more than twenty years in age. No investigations were originally conducted and no special precautions implemented. In fact, poor and inadequate water precautionary measures prevailed on these sites. Follow-up stability investigations have subsequently indicated that most of these sites may be characterised as displaying a medium to high risk of sinkhole formation. The important point is that an inappropriate density and type of development in relation to the risk characterisation was permitted. The remedial work on a site may run into hundreds of thousands of rands. Examples are given below:

EVENT	DATE	CAUSE	REMEDIAL COSTS
Aircraft Hanger 4	1989	Leaking Service	R 350 000
Concrete paving for aircraft	1986	Leaking Service	R 500 000

A three storey structure in Irene suffered distress as a result of ground movement associated with the ingress of water during 1979. The replacement value of the structure in 1981 was in the region of R4 million. Appropriate precautionary measures had to be taken. Expenditure on these measures exceeded R500 000 (1981 prices). These precautionary measures included placement of services in ducts and general improvement to the drainage of the site. The complex was of inappropriate design in relation to the risk characterisation of the area.

An attempt to secure a strategic complex of approximately 10ha, inappropriately positioned in a high risk area in Voortrekker-hoogte, entailed expenditure to the tune of R3 million during the early 1980's. Inappropriate water bearing services originally installed in the complex had deteriorated giving rise to disruptive stability problems. A multistoried structure valued at R4 million had to be demolished after a sinkhole developed under the foundations in 1978. The complex was so distorted that it was declared unsafe for occupation.

A block of flats in the Midrand area had to be demolished due to irretrievable damage to the structure. A sinkhole developed under the building during mid December 1986.

In the Vosloosrus area, approximately R100 000 has been spent on remedial work and in excess of R300 000 on precautionary measures in an attempt to secure an area within a R4,8 million complex. Four sinkholes have fallen in the area within a period of one year. The remedial work involved backfilling sinkholes and the precautionary measures entailed placement of waterbearing services in sleeves and sealing surface areas around buildings. The structure was apparently incorrectly sited on a tract of ground not previously investigated. A recent stability investigation reveals that the site may be characterised as displaying a high risk of sinkhole formation.

Financial losses incurred in dolomite areas of the East Rand, West Rand and south of Pretoria exceed R120 million during the last twenty years. The figure refers only to losses incurred due to damage to major structures (hangers, multistoried buildings, etc) and infrastructural elements (roads). Losses due to delays, loss of revenue, loss of production, detours, etc have not been taken into account.

It can be ascertained from the data presented in this section that there are costly financial ramifications to the process of haphazardly developing on dolomite. These data serve to underscore the fact that investigations are a prerequisite for preservation of life and for financial reasons. It is imperative that areas proposed for development be characterised in terms of risk and that appropriate development be instituted in relation to the risk.

2.7 Standards and ordinances

The Geological Survey, the State Co-ordinating Technical Committee on Sinkholes and Subsidences, Mining Houses, Universities and individual consultants have encouraged research, set standards and have done much to restore confidence in dewatered and non-dewatered areas. It is imperative that as the pressure mounts for land to be made available for residential development particularly low cost housing and as intensive development encroaches on the girdle of dolomite around of the PWV, standards and precautions are relaxed or ignored.

In the Transvaal, Clause 17 of Provincial Ordinance 25 of 1965 was devised to "co-ordinate and harmonise development. To ensure safety, peace of mind and the general well being of the populace...as well as effective and economic development". The public must have confidence, once a township is proclaimed, that there are no hidden dangers attached to the land they have purchased. The Provincial Gazette Extra-ordinary of 10 June 1986 repealed Ordinance 25 of 1965 embracing the philosophy and requirements for investigations and engineering services in a new consolidated Ordinance known as The Planning and Township Ordinance 20 of 1986.

Urban development on dolomite is feasible. There will, however, always be risk attached to such development. The important points to consider though are that:

1. The type of selected development must be appropriate in relation to the stability conditions prevailing on the site.

2. The risk must be of an acceptable order and remain so.

3. The costs of the precautionary measures must not be inordinately large in relation to the overall financial investment in the development.

Prior to consideration for development, sites must be subjected to stability and shallow foundation investigations. The purpose of the investigation is to characterise the stability conditions on the site in terms of the risk either of sinkholes forming or ground movement occurring. Sites are usually classified as displaying either a low, medium or high risk of sinkhole forming or ground movements occurring. The particular type of development selected in relation to the risk is critical to the safe and long term viability of the selected development.

3. A REVIEW OF EXISTING CLASSIFICATION SYSTEMS UTILISED FOR THE EVALUATION OF SITES ON DOLOMITE

A number of classification systems have been developed by various authors during the 1970's and 1980's to facilitate the process of evaluating the stability of sites. These approaches have been systematic guides to the discussion and analysis of conditions prevalent on sites. These classification systems aim to group areas displaying similar geological and geotechnical conditions and to assign risk values to these groupings. These systems obviously must serve to improve communication. Furthermore Venter (1981) emphasises that these systems should provide quantative data for the design of buildings, including precautionary and rehabilitative measures. A selection of these classification systems are presented and reviewed in this chapter.

3.1 The Weaver (1979) x - Factor classification system

Weaver (1979) proposed that the stability of sites be classified using an empirical method based on information obtained from borehole information. The method is suggested for use in the interpretation of conditions in boreholes that are less than 30m in depth. If the boreholes is of greater depth than 30 m, the deeper information is ignored.

A stability factor designated x, is calculated for each borehole. The x factor is the ratio of depth to wad in the profile over the total thickness of wad. Boreholes with no wad present are assigned a x factor value of infinity.

The x values of all the boreholes on the site are determined and contour lines are drawn for the x values of between 1 and 4. In this manner the site is divided into three zones with values interpreted as denoting the following conditions:

- Highly Unsuitable - $X < 1$
- Doubtful - $1 < X < 4$
- Suitable - $X > 4$

Comment:

This system was one of the first developed to evaluate sites on dolomite. At that stage little was known of the so called "wad" (residual dolomite) and the material was viewed as possessing only negative engineering geological properties.

Weaver (1979) was, in the context of the state of the art at that time, attempting to provide a framework for evaluating the presence of this "poor" material in the profile. It is important to note that the term "wad" has traditionally been used to denote a wide range of soil materials. Investigations have been guided by "worse case" properties, requiring only the presence of a black coloured soil in a profile to justify a poor characterization of its geotechnical state. Buttrick (1986) has concluded a detailed geochemical and geotechnical study of the weathering products of dolomite i.e., the so called "wad and ferroan soils". The study emphasised that the terms "wad and ferroan soils" were merely omnibus expressions describing a range of materials with widely divergent geotechnical characteristics, ranging from poor to very good. These materials are merely clays, silts or sands with certain properties, and have to be treated accordingly. Buttrick (1987) indicated that there may in fact be more hazardous materials in the profile when reviewing stability. Experience has indicated that gap graded materials such as chert rubble and fines (clay (wad), silt (wad) or terra rosa), must be treated with circumspection.

In the application of Weaver's classification system, the gap graded materials are reviewed in a positive light; that is as enhancing stability.

The following vital information is also not taken into consideration:

(i) Waterlevel, which is critical with respect to stability in a dewatering and non-dewatering scenario.

(ii) Receptacle development.

(iii) Nature of other soil materials in the subsurface profile which may either enhance or detract from the stability characterization.

The practice of adding together the thickness of the various layers of "wad" in the profile to constitute a single layer of the summated thickness is most unsatisfactory. Five layers of "wad of 0,2m thickness scattered at varying depths in the profile will not necessarily behave in the same manner as a single layer of 1m thickness.

This classification system has been used with some success in certain areas, but appears to oversimplify the evaluation procedure if applied universally.

3.2 A Classification approach proposed by Venter (1981)

Venter (1981) notes that a classification for dolomite sites should attempt to:

i) Subdivide the dolomite geology into groups of similar behaviour in 3 dimensions.

ii) Create a basis for the understanding of the characteristics of each group.

iii) Provide quantitive data for the design of the foundations of buildings, either precautionary or rehabilitative.

iv) Provide a basis of communication.

A comparison of inducive and inhibiting factors with respect to instability events gives an indication of the suitability of the site for a certain use. Venter (1981) suggests that the degree of suitability of a site will vary according to different proposed usages. The inhibiting and inducive factors are defined as follows:

1) Inhibiting factors.

The most important inhibiting factors are the strength and the potential resistance to erosion of the overburden material. The greater the strength of the overburden material, the greater is the ability of the material to bridge any voids in the residuum.

The strength aswell as the erodibility of the material are functions of the factors indicated in Figure 10. The less erodible the material the less likely is the process of internal erosion to occur. The thickness of the overburden material is also regarded as crucial (Venter 1981). The thinner a layer the less significant it will be. If the overburden is very thin, the characteristics of the bedrock are of importance.

2) Inducing factors.

Venter (1981) indicates that the following factors

SEE "OMSTANDIGHEIDSFAKTOR" IN TABLE 7 FOR ASSIGNED VALUES

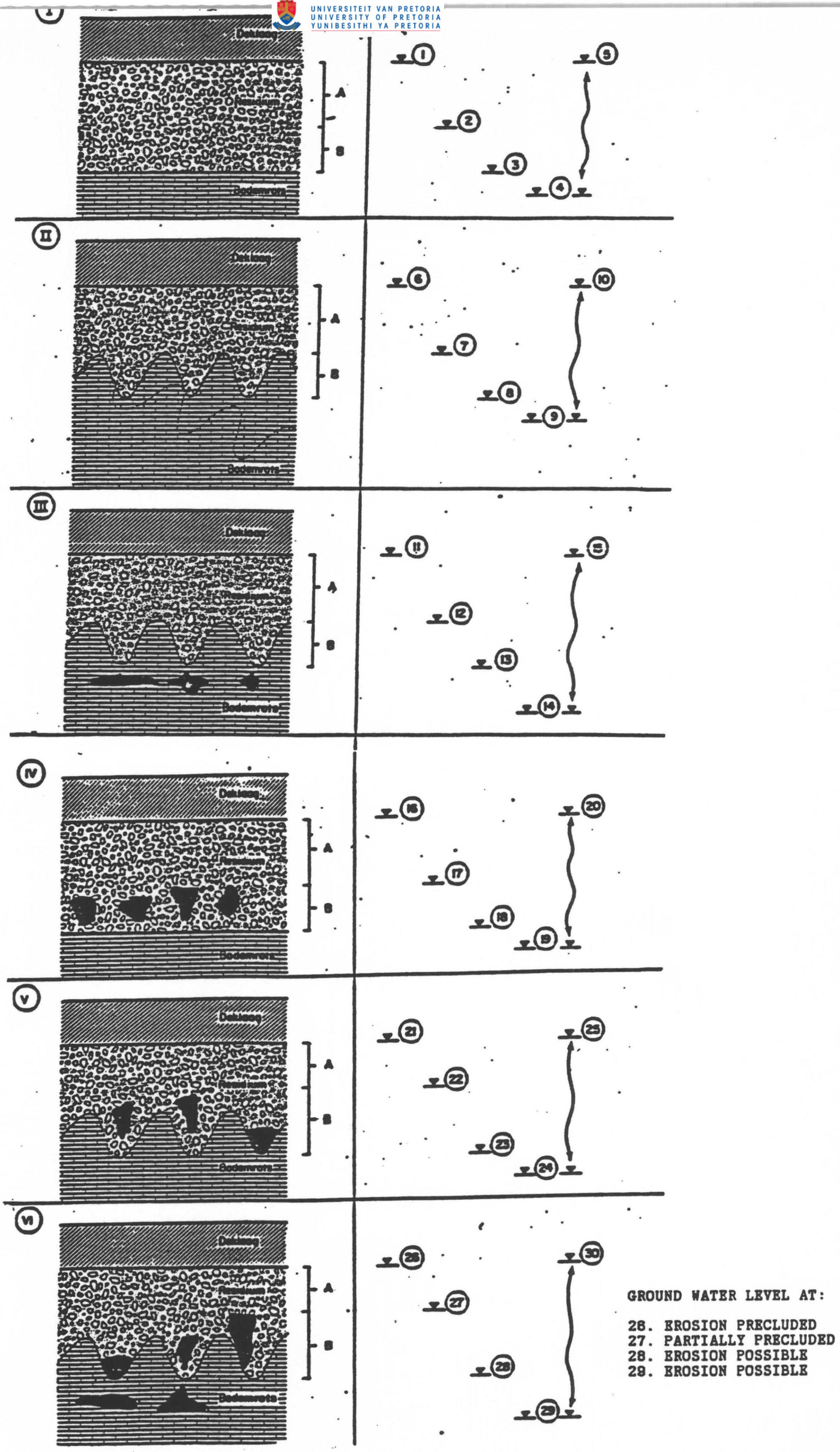


Figure 10: Possible positions which the watertable can assume with respect to any cover layer, residuum and the bedrock (After Venter 1981).

may increase the probability of ground movement:

i) The bedrock gradient.

ii) The pinnacled nature of the bedrock.

iii) The degree of cavitation in the bedrock.

iv) The degree of void development in the overburden.

Venter (1981) gives an indication of what values these factors can assume. (Figure 11, 12, 13, 14 and 15).

The position of the groundwater table in the sub surface profile is noted by Venter (1981) to be important. It is apparent that the factors will have individual as well as an interrelated, combined influence on potential instability events.

Venter (1981) points out that if a single factor were to change in either magnitude or intensity, it is possible that the character of the entire geological millieu will change and consequently the nature of the instability event. Prior to classifying a dolomite terrain, it is essential that the area is sub-divided into zones of engineering geological homogeneity.

All factors discussed above are incorporated in Table 7. Each factor is subdivided into five categories. Each category is assigned a value depicting its relative importance in terms of the probability that there is a direct correlation between the factor and potential ground movement. Venter (1981) indicates that although the strength and potential erodability of the overburden material are presently viewed as equally important, this may not necessarily be the case.

Venter (1981) proposes the use of a value reflecting the ratio of the overburden to the void free residuum A and the thickness of the layer residuum B containing voids. If the ratio is large, the relative importance of such factors as the bedrock gradient, the pinnacled nature of the bedrock etc., is of less importance. Alternatively, the smaller the ratio, the more significant the influence of the bedrock variable.

The sum of all factors gives a "grand total". The significance

The influence of STRENGTH on arching

Rock Material

1. **Type of Material**
2. **Degree of Weathering**
   - Completely weathered
   - Highly weathered
   - Medium weathered
   - Slightly weathered
3. **Jointing and rock mass strength**

   Categories:

   - Strong rock mass
   - Average rock mass
   - Weak rock mass
   - Very weak rock mass

4. **Penetration Rates**

   Categories:

   - Very strong
   - Strong
   - Average
   - Weak
   - Very weak

Soil Material

1. **Moisture content**
2. **Colour**
3. **Consistency**
4. **Structure**
5. **Soil type**
6. **Origin**

$$S = C + \sigma \tan \phi$$

Figure 11: Factors influencing the strength of geological materials (after Venter 1981).

ROCK MATERIAL	**SOIL MATERIAL**
(i) Degree of consolidation and cementing	(i) Grading
(ii) Degree of weathering	(ii) WAD content - High - Medium - Low
(iii) Jointing - very closely jointed - closely jointed - medium jointed - widely jointed - very widely jointed	(iii) Wad 'condition' - dense - loose
(iv) Permeability	(iv) Permeability

Figure 12: Factors influencing the resistance to erosion of geological materials (After Venter 1981)

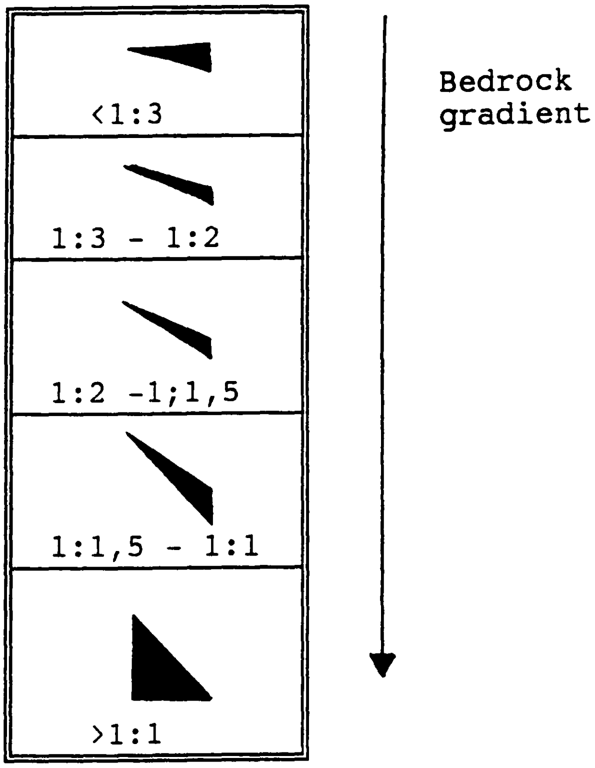


Figure 13: Different magnitudes of bedrock gradient (After Venter 1981)

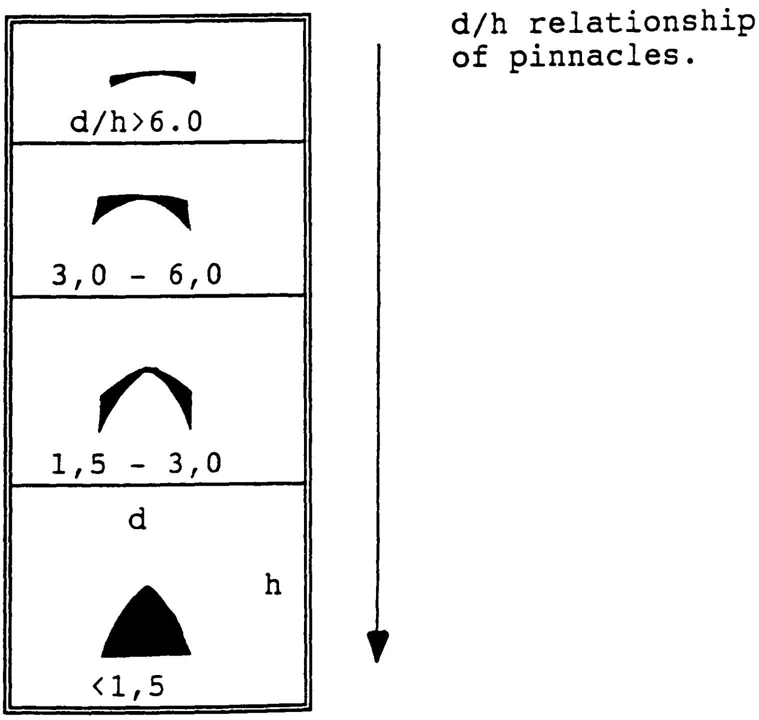


Figure 14: Different magnitudes of pinnacle development (After Venter 1981).

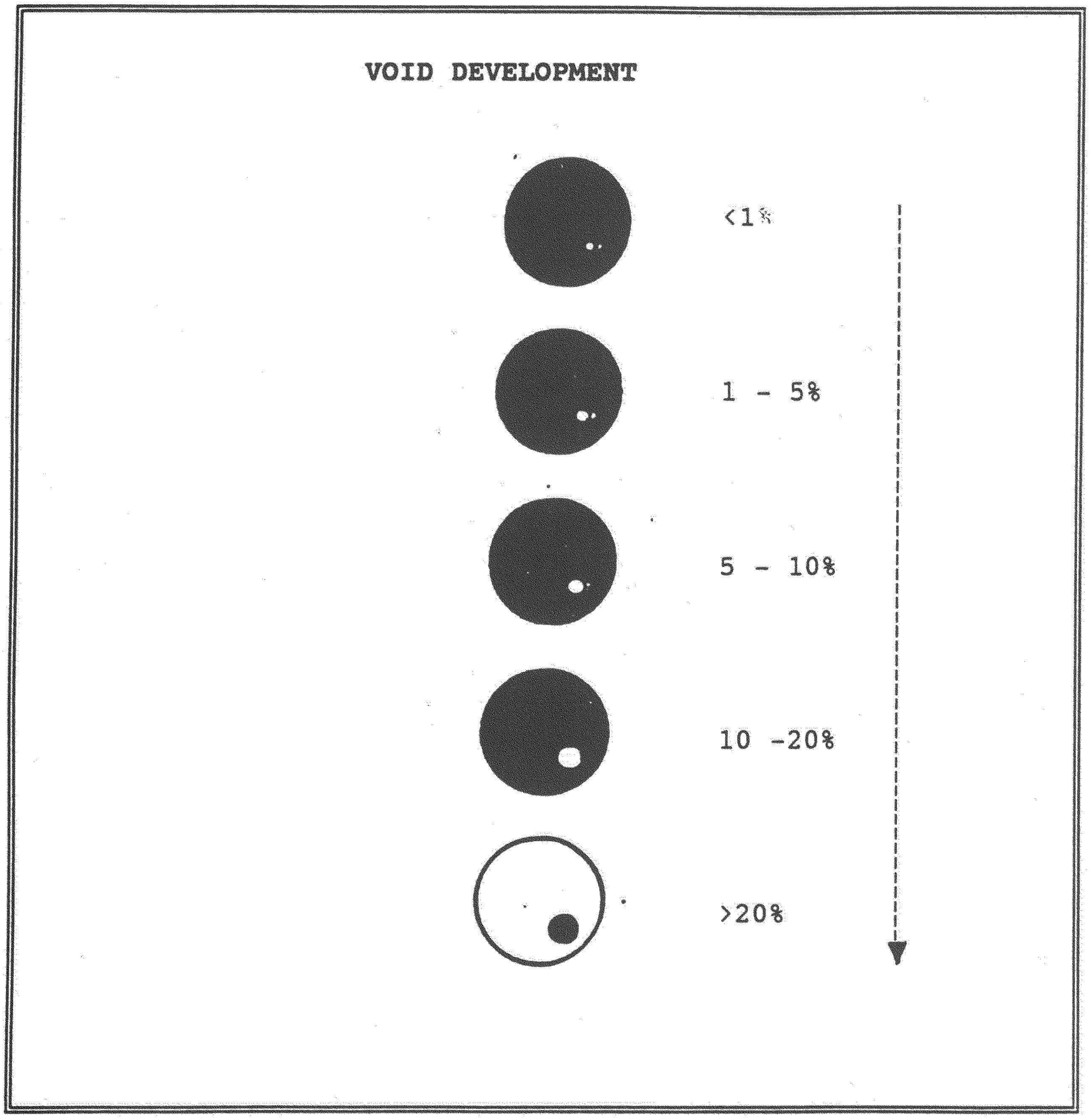


Figure 15: Different degrees of void development (After Venter 1981)

STRENGTH VALUE A	VERY WEAK 7	WEAK 10	MOD. STRONG 12	STRONG 15	VERY STRONG 18
ERODIBILITY VALUE B	HIGHLY ERODIBLE 7	ERODIBLE 10	MODERATELY ERODIBLE 12	LOW ERODIBLITY 14	VERY LOW ERODIBLITY 16
THICKNESS X THICKNESS VALUE C THICKNESS FACTOR T	0 - 3m 0.6 3X ――― X+Y+Z	3 - 12m 0.7 3X ――― X+Y+Z	12 - 30m 0.8 3X ――― X+Y+Z	30 - 60m 0.9 3X ――― X+Y+Z	>60m 1.0 3X ――― X+Y+Z
STRENGTH VALUE D	VERY WEAK 7	WEAK 10	MOD. STRONG 12	STRONG 15	VERY STRONG 18
ERODIBILITY VALUE E	HIGHLY ERODIBLE 7	ERODIBLE 10	MODERATELY ERODIBLE 12	LOW ERODIBLITY 15	VERY LOW ERODIBLITY 16
THICKNESS Y THICKNESS VALUE F THICKNESS FACTOR Z	0 - 3 0.6 3Y -------- X+Y+Z	3 - 12 0.7 3Y -------- X+Y+Z	12 - 30 0.8 3Y ---------- X+Y+Z	30 - 60 0.9 3Y --------- X+Y+Z	> 60 1.0 3Y -------- X+Y+Z
STRENGTH VALUE G	VERY WEAK 7	WEAK 10	MOD. STRONG 12	STRONG 15	VERY STRONG 16
ERODIBILITY VALUE B	HIGHLY ERODIBLE 7	ERODIBLE 10	MODERATELY ERODIBLE 12	LOW ERODIBLITY 14	VERY LOW ERODIBLITY 16
THICKNESS I THICKNESS VALUE R THICKNESS FACTOR P	0 - 3 0.6 3I ――― X+Y+Z	3 - 12 0.7 3I ――― X+Y+Z	12 - 30 0.8 3I ――― X+Y+Z	30 - 60 0.9 3I ――― X+Y+Z	> 60 1.0 3I ――― X+Y+Z
BEDROCK GRADIENT IF C + F > 0.8 0.4 - 0.8 0.4	>1:1 -3 -4 -5	1:5 - 1:1 -2 -3 -4	1:2 - 1:5 -1 -2 -3	1:2 - 1:3 0 -1 -2	< 1:3 0 0 0
d/h RATIO IF C + F > 0.8 0.4 - 0.8 < 0.4	-2 -3 -4	< 1.5 -2 -3 -4	1.5 - 3.0 -1 -2 -3	3.0 - 8.0 0 -1 -2	> 8.0 0 0 0
VOID DEVELOPMENT RESIDUUM B IF C + F > 0.8 0.4 - 0.8 0.4	> 20% -4 -5 -6	10 - 20 % -3 -4 -5	5 - 10 % -2 -3 -4	1 - 5 % -1 -2 -3	< 1% 0 -1 -2
BEDROCK VOID DEVELOPMENT IF C + F > 0.8 0.4 - 0.8 0.4	> 20% -4 -5 -6	10 - 20 % -3 -4 -5	5 - 10 % -2 -3 -4	1 - 5% -1 -2 -3	< 1% 0 -1 -2
CIRCUMSTANCE FACTOR	12 - 30	31 - 50	51 - 70	71 - 90	91 - 100
GRAND TOTAL OF ASSIGNED VALUES	0 - 20	20 - 40	40 - 60	60 - 80	80 - 100
RISK CATEGORY	VERY HIGH	HIGH RISK	MEDIUM RISK	LOW RISK	VERY LOW
PERMITTED DEVELOPMENT	NO DEVEL-OPMENT	LOW COST	HIGH COST	HIGH COST	HIGH COST

Table 7 : Dolomite zonal risk classification (After Venter 1981).

of the total is expressed in terms of the expected number of sinkholes or subsidences that will potentially occur within a twenty year period within an area of one square kilometre (Table 7). Permitted development types are given in relation to the various grades of risk. Venter (1981) also suggests possible special founding or stabilisation methods for high cost/high maintenance developments.

Comment

This system reflects a detailed and thorough consideration of the many complex interrelated factors influencing the stability of a dolomite site. It is the author's opinion that this system is one of the most comprehensive produced to date. Venter (1981) indicates, however, that water management, which is the single most important factor governing whether movement occurs, is excluded from this classification system.

To determine the susceptibility of the profile to ground movement must surely imply that the materials of the profile are subjected to either the percolation or withdrawal of water. To evaluate the potential resistance to erosion ("erosie bestandheid") of materials it is necessary to establish the permeability. This assessment is either made directly, or based on experience or laboratory data. In effect, therefore, the materials in the subsurface profile are being evaluated under the influence of a head of water simulating what is to be expected when water ingress occurs.

In the mind of the evaluator, the profile is being subjected to poor water management, water is envisaged as passing through the profile. The determined risk grade (very low to very high risk) is consequently based on the most conservative assessment.

Dewatering does not appear to be embraced in this classification system. Although the author alludes to the importance of the position of the watertable, it is not included in the weighting process.

The application of the system requires the prediction of void development on a scale of <1% to >20%. Unfortunately neither geophysical nor any other method exists to predict void development.

According to Venter (1981) the pinnacled nature of the bedrock is of particular relevance in areas of shallow bedrock. In areas where the bedrock is covered by a substantial blanketing layer, the importance of this characteristic diminishes.

This classification system places great emphasis on the bedrock gradient. Experience indicates that this factor is particularly important in areas subjected to dewatering. Unfortunately this system fails to embrace the process of water level drawdown. The bedrock gradient is less important in the case of areas not being subjected to dewatering. Based on a study conducted south of Pretoria, Schoning (1990), indicates that there is no preferential occurrence of sinkholes on any particular gravity anomaly (i.e., gravity high, low or gradient).

It must be emphasised, however, that Venter (1981) has repeatedly stated that this system was particularly designed to stimulate thought and debate.

3.3 Wagener's (1982) method of classes.

Wagener (1982) proposes that dolomite sites be classified according to the thickness of the overburden layer. This layer occurs between the soil surface and the average level of dolomite pinnacles and floaters. Evaluation of the thickness of the overburden gives an indication of potential settlement problems. Three types of settlement can be distinguished.

(i) Normal settlement due to a combination of immediate elastic settlement and consolidation settlement.

(ii) Sudden subsidence settlement due to the appearance of a sinkhole caused by the collapse of an arch, which spanned over a cavity in the residuum.

(iii) Gradual subsidence settlement or doline formation due to the formation of a slow subsidence over a cavity or weak zone in the residuum, where an arch is not able to form.

Wagener (1982) indicates that a site may be divided into three categories on completion of the field work and the evaluation. Classes A, B and C are utilized to denote these categories as follows:

Class A: Pinnacle and boulder dolomite either at or near the surface. 0< C< 3m.

Class B: Pinnacle and boulder dolomite overlain by moderately thick soil cover. 3m<C<15m.

Class C: Pinnacle and boulder dolomite overlain by thick soil cover. C>15m.

In the above classification C refers to the average thickness of overburden to the tops of the pinnacles and boulders.

The zonation of the site in terms of the above three classes is executed on the basis of information obtained from remote sensing, gravity surveys, borehole data, test pits and laboratory tests.

Based on the selected category, it is considered possible to quantify the types of settlement and propose appropriate solutions to withstand expected movements. Wagener (1982) suggests the following solutions in relation to the three classes defined above:

	FOUNDATION DESCRIPTION	SITE CATEGORIES
(i)	Conventional foundations	Class A, B & C
(ii)	Mattress of improved earth	Class A, B & C
(iii)	Founding on pinnacles	Class A, B & C
(iv)	Piling	Class A
(v)	Shafts	Class B & C
(vi)	Caissons	Class B & C
(vii)	Special founding methods	
	a) Dynamic consolidation	Class B & C
	b) Reinforced earth	Class B & C
(viii)	Special structures	
	a) Reservoirs	Class A, B & C
	b) Slimes Dams	Class A, B & C

Comment

Wagener (1981) indicates that the field investigation culminates in the sub-division of the site into the categories or classes listed above. The intention is to quantify the three types of movement and permit the adoption of a foundation solution.

This system does not embrace the following factors:

- (i) ground water level/s
- (ii) possible movements of the water level or the activities of other mobilising agencies
- (iii) the nature of the materials blanketing the dolomite bedrock
- (iv) receptacle development

This system is based on the premise that the selection of an appropriate construction method will preclude stability problems. It is believed that this system should be viewed as an excellent guide to the selection of appropriate construction methods once the stability conditions on the site have been evaluated.

The design of the foundations of a structure is not the sole purpose of conducting a stability investigation. Townships consist of many infrastructural elements such as roads, walkways, parks etc. To secure the integrity of the structure alone will not suffice. People may be at risk in the open areas around the buildings. The characterisation of the stability of an entire site permits the selection of appropriate township/development design structure and foundation design and water precautionary measures.

3.4 A classification method proposed by De Beer (1981).

De Beer (1981) indicates that the evaluation of dolomite areas is affected by assessing certain "influencing factors" that may have had an affect on the site in the past or that may still effect a site during its development. The "influencing factors" are grouped into three classes:

- (a) Natural influencing factors
- (b) Historical, occupational influencing factors
- (c) Future occupational influencing factors

De Beer (1981) states that these factors should be regarded as a check-list to be considered when evaluating a site. A rating of 1 to 5 is applied to each of the individual factors within the three main groups of influencing factors.

One represents the most favourable condition and 5 the most adverse condition. The individual factors are rated equally compared with each other but any one factor may emerge as an overriding factor. All the factor ratings are finally added and the total serves as an indicator of risk of damage (De Beer 1981).

The proposed subdivision of the influencing factors and the designated ratings are elaborated on below:

(i) Natural influencing factors.

(a) Watertable.

1 Static and shallow
3 Static and at bedrock level
5 Static and at considerable depth below bedrock

(b) Geology - depth of bedrock.

1 >30 m
3 Around 15 m
5 Outcropping to less than 10 m

(c) Geology - strength and permeability of surface material.

1 Well developed pedocrete or Karoo shale blanket
3 (No definition given by De Beer (1981)).
5 Wad and waddy dolomite within 1,5 m of ground surface

(d) Geology - nature of intervening residual materials.

1 Mainly chert.
2 Wad and chert.
5 Mainly wad.

(ii) Historical occupational influencing factors.

(a) Relative frequency of damage.

1 No known sinkhole nor doline occurrence within 10 km of the site.
Newly developed area, less than 5 years old.
3 (No definition given by De Beer (1981)).
5 Sinkhole or doline occurrences on site or within 50 m of site. Development in immediate vicinity of site for at least 20 years.

(b) History of drainage of site.

1 Natural undisturbed gently sloping grassland, no previous development, no ploughing.
3 Gently sloping topography, residential development, no buried stormwater reticulation e.g. Tembisa, Kathlehong.

5 Either industrial or residential development with septic tanks, french drains, buried stormwater reticulation, well watered gardens (e.g., Valhalla).

Is there a relationship between rate of water consumption and sinkhole incidence?.

(iii) Future occupational influencing factors.

(a) Proposed disturbance of ground surface and natural drainage.

1 None.
3 Removal of pedogenic blanket.
5 Deep cuts exposing wad, pinnacles and voids.

(b) Proposed structure.

1 Railway line.
2 Special residential with shallow foundations
3 Dairy, brewery, factory etc., where large quantities of water are to be used.
4 Concrete reservoir.
5 Unlined dam.

(c) Knowledge of geological conditions.

1 Infra-red photography, gravity, test pits, trial holes, boreholes, shafts.
3 Test pits, trial holes and boreholes
4 Test pits only.
5 No investigation.

As stated earlier, the factor ratings are added and grouped into the following broad categories of risk of damage:

0-1	LOW
16-30	MODERATE
31-45	HIGH

The site is then divided into zones or areas of varying degree of risk of damage.

Once such an evaluation of the site has been completed it has to be related to the Damage Acceptability of the Structure which is the soil-structure interaction (De Beer 1981).

(iv) Damage acceptability (soil structure interaction)

- Minor cracking - filling and repairing of cracks - operations unaffected, inconvenience only.
- Damage to walls and finishes requiring extensive repairs - operation unaffected but major inconvenience.
- Major damage to structure - temporary cessation of operation during repairs.
- Major damage to structure or abandonment of parts of structure - cessation of operations for long periods.
- Damage to structure cannot be tolerated, (e.g., hospital, nuclear power station).

Either the property owner or developer has to be intimately involved in decisions concerning "acceptable damage" to the proposed development during to the final evaluation of the site.

Comment:

This detailed and thorough system is particularly aimed at provoking thought and ensuring that the evaluator is considering the key factors influencing the stability of a site.

Comment with respect to the four categories of influencing factors is as follows:

(a) Watertable: De Beer (1981) views a static and shallow watertable as most favourable situation and the least favourable a watertable which is "Static and at considerable depth below bedrock". The qualification "Static" implies that the system does not allow for lowering of the waterlevel.

Within the context of a dewatering scenario the shallow groundwater level could represent the most unfavourable situation.

A static watertable at considerable depth below bedrock may present a very unfavourable stability situation if potentially erodible soil materials blanket the bedrock in a non-dewatering and dewatering scenario. In both scenarios, ingress water may cause damage to the subsurface profile.

(b) Geology - depth of bedrock:

Depth to bedrock is crucial for three reasons:

(i) Depth to receptacles in bedrock.

(ii) Depth to an incompressible medium (dewatering scenario).

(iii) Depth to the bedrock/soil interface where preferential erosion may occur along potential flow paths. (Non-dewatering scenario).

The location of either receptacles or disseminated receptacles should perhaps be viewed as a more important criterion than bedrock depth. Disseminated receptacles, particularly, may be located above bedrock level. Water level is important with respect to receptacle depth in both a dewatering and non-dewatering scenario and with respect to bedrock in the former.

(c) Geology - strength and permeability of surface material:

It must be noted that the well developed pedocrete or Karoo shale may be favourable in a non-dewatering scenario but may not be adequate to create favourable conditions in a dewatering scenario.

So called wad may, if correctly constituted, enhance stability. Experience indicates that clay (wad) may in fact be less susceptible to subsurface erosion than some of the gap graded materials such as the combinations of chert rubble and fines.

(d) Geology - nature of intervening residual materials:

(i) De Beer (1981) indicates that he views intervening residual materials, mainly of chert, as the most favourable condition, "wad and chert" as intermediate and "mainly wad" as the most adverse condition. Experience indicates that gap graded materials possess a multitude of potential flow paths which may be exploited by percolating water resulting in subsurface erosion. Clay soil materials (e.g. wad and ferroan soils) may in fact enhance stability if characterised by a low permeability. The nature of the soil material must first be established.

(ii) Comments concerning "wad" made in the section (a) of this chapter (X-Factor classification system) are most pertinent here.

(iii) An important point with respect to De Beer's (1981) historical occupational influencing factors is the context in which the assessment is made. Is the site and environs presently not dewatered, has it either already been dewatered or is it being dewatered (i.e., will the scenario change during the lifetime of the development?).

(iv) With respect to the "relative frequency of damage", the category "no known ground movement event occurrence within 10km of the site: and a newly developed area, less than 5 years old" is viewed as the most favourable by the author. It must be noted, however, that the degree of disturbance of the metastable environment is crucial as is the age of the development. As the services age, so leaks and instability events occur. Thus, the past (less than 5 years) and present is not necessarily the key to the future as the crucial age (greater than 20 years) has not been achieved in surrounding developments. A comparison should also be confined to similar subsurface conditions and the same geological formation. No events of instability on a "natural undisturbed gently sloping grassland of no previous development or ploughing" should not imply that the area may be viewed positively. The author is implying that the fact that the environment has as yet not been subject to abuse, is a very positive factor. Unfortunately it is man's influence and disturbance of the environment that reveals its susceptibility to sinkhole and doline formation. Consequently a virgin tract of land may, in fact, present no advantage in terms of revealing its susceptibility, but it certainly is an advantage to initiate appropriate development on such a virgin tract of land.

3.5 Van Rooy's (1984) MF-Classification System.

Van Rooy (1982) attempted to develop a new classification system in order to evaluate information derived from existing investigation techniques applied during the assessment of sites on dolomite. This system is termed the Multiple Factor System or MF-Classification System. The system encompasses the following factors:

- Drainage history.
- Gravity contour features.
- Depth to wad.
- Thickness of wad.
- Characteristics of the wad.
- Type of material above the first appearance of wad.
- Type of material below the base of the wad.
- Damage: Historical record.
- Future development.

Van Rooy (1984) proposes the use of classification parameters which may be defined as follows:

(i) Classification utilising surface information: The great lateral and vertical variation of subsurface conditions in karst areas precludes a drilling programme that ensures that all possible conditions are intercepted and delineated. It is, thus, important to initially subdivide the site into similar geological zones. This subdivision is executed utilising geological maps, air photographs and stratigraphic information.

The following manifestations are delineated: Outcrop areas, chert-gravel zones, areas of similar vegetation cover, old sinkhole zones, subsidence areas, scattered outcrop areas, different formations and intrusives.

(ii) Classification utilising thermal infrared linescan. Van Rooy (1984) suggests that the following risk characteristics are assigned to tonal variations, on the thermal infrared linescan imagery:

Zone (Tone)	Risk
Black	Very High
Dark Grey	High
Grey	Medium
Light Grey	Low
White Grey	Very Low.

It is noted that the information must be carefully evaluated. The imagery is of no use in developed areas or on small sites. Vegetation, topography and geology all influence the imagery. An aspect of great influence on sinkhole formation is the drainage of an area. Thermal infrared linescan imagery can prove of great value in delineating areas of poor drainage. Van Rooy (1984) contends that all these areas of poor drainage may be regarded as high risk areas.

(iii) Classification utilising gravity information Features on the gravity contour map permit the identification of four basic zones:

Gravity "high" anomalies
Gravity "low: anomalies
Steep gradient zones
Gentle gradient zones.

Generally this subdivision of the gravity permits the formulation of an impression of the bedrock topography on the site. Confirmation of conditions within these zones by the selective placement of boreholes ultimately limits the amount of drilling required.

(iv) Classification utilising borehole data. Borehole information is used to subdivide the following factors into five classes of differing conditions:

- Depth to wad.
- Total thickness of wad.
- Characteristics of the wad.
- Type of soil material overlying the first occurrence of wad.
- Type of soil material below the base of the wad.

A value of 0,25 to 4 is assigned to each condition ranging from poor to very good. Each factor's value is assessed based on borehole information. (Table 8). These values are then multiplied.

The classification of borehole information is subdivided into two broad categories namely those holes containing wad and those not. By evaluating the abovementioned factors for each borehole a stability value is calculated.

Van Rooy (1984) notes that the following aspects must be borne in mind when values are assigned to the various factors:

a) The description of various materials in the profile must firstly be grouped into zones of the same characteristics e.g., colour variations in either chert breccia or shale are not distinguished.

b) If more than one layer of wad occurs in the profile, the thicknesses of the various layers are added together to obtain a total thickness. The properties of the poorest layer are utilised in the assessment of the stability value calculation.

c) The depth to wad is taken as the depth to the first layer of wad in the profile.

d) The depth of a borehole also plays a role. Thirty metres is assumed to be the standard borehole depth for this system. The influence of material deeper than thirty metres is regarded negligible.

Table 8: Ratings for boreholes containing wad (After Van Rooy, 1984).

ASSIGNED VALUE	DEPTH TO WAD	TOTAL THICKNESS OF WAD	PROPERTIES OF WAD	MATERIAL ABOVE FIRST OCCURRENCE OF WAD	MATERIAL BELOW LAST OCCURENCE OF WAD
4	D>15	A≤1	High penetration resistence e.g. chert with little wad approx. (15%)	Material with a very high strength e.g. dolomite	Unweathered rock
2	12<D≤15	1<A≤2	Chert with 30% wad. Dolomite with wad	Competent material e.g. leached dolomite with 30% red soil	Leached dolomite. Chert weathered.
0,75	8<D≤12	2<A≤3	Wad with 30% Chert	Moderate. strong e.g. red soil with 30% Chert	Jointed dolomite. Chert with red soil
0,5	3<d≤8	3<a≤5	Wad with little penetration resistance	Low strength material red soil shale sand	Red soil with chert
0,25	D≤3	A>5	Cavity wad with little or no penetration resistance	Material with poor strength silt / clay	Cavities in dolomite. Pinnacled dolomite

e) If there are horizons with different properties above and below the wad layer, an average value is calculated for the various horizons. The average value then serves as the factor for the:

i) Material above the wad.
ii) Material under the wad.

Table 8 presents the proposed values for the subdivision of boreholes with wad. Table 9 indicates proposed values for the subdivision of boreholes which do not contain wad.

Borehole stability values are subdivided into intervals relating to designated risk grades with respect to sinkhole information (Table 10).

Three different values can be assigned to each material type in Table 9 namely:

a) Where the material type occupies the entire profile.

b) Where the layer of a particular material type is thicker than 10 metres.

c) Where the layer of a particular material type is thinner then 10 metres.

(v) Classification utilising damage to structures
Damage to structures existing either on the site under investigation or on adjacent sites can be utilised to identify poor zones where instability events can be expected. Obviously a distinction must be drawn between damage due to poor construction methods and unstable foundation conditions. Only the latter is considered here.

Van Rooy (1984) suggests the subdivision as presented in Table 10. The assignment of a risk grade to this factor must be exercised with caution. Other factors such as poor drainage around the building, leaking water bearing services the utilisation of the building, may play a role.

Table 9: Borehole stability value intervals with corresponding sinkhole risk grade (After Van Rooy, 1984).

Borehole stability values			Risk
0	-	0,0024	Very High
0,0025	-	0,124	High
0,125	-	0,5624	Moderate
0,5625	-	15,0	Low
16,0	-	256	Very Low

Table 10: Ratings for boreholes not containing wad (After Van Rooy 1984).

Material Type		Assigned Values		
		Entire Profile with 1,5m Alluvium	Portion of Borehole Profile With:	
			> 10 m	< 10 m
Dolomite:	Unweathered	20	8	4
	Weathered	16	5	2
	with Chert	16	5	2
Chert Breccia / Gravel:				
	Weathered	20	8	4
	With Red Soil	15	4	2
	With Shale	20	8	4
Shale:	Unweathered	20	8	4
	Weathered	15	4	2
	With Breccia	20	8	4
Intrusive Rock:				
	Unweathered	20	8	4
	Weathered	8	4	2
	Completely weathered clay	0,15	0,25	0,5
Red Soil:		0,5	0,5	0,75
	With Chert	2	1	1
Sand:		8	2	1
Silt:		0,5	0,5	1
Clay:		0,5	0,5	1
General:	Very Strong	16	8	4
	Strong	0,6	4	2
	Moderately Strong	0,13	0,5	0,75
	Weak	0,12	0,25	0,5

CRACK WIDTH K (mm)	DEGREE OF DAMAGE	RISK GRADE
$K>10$	Severe damage	Very high
$5<K\leq 10$	Moderate damage	High
$2,5<K\leq 5$	Visible damage	Moderate
$0<K\leq 2,5$	Little damage	Low
$K=0$	No damage	Very low

Table 11: Categories of structural damage (After Van Rooy,1984).

(vi) Final stability zoning.
All the stability and risk values are depicted on a map of the site. The site is then subdivided into risk zones namely very high, high, medium, low and very low risk zones.

In summary, the final risk zoning is constituted as follows:

a) Sub-division of the site by means of surface information, drainage history and gravity contour features.

b) Confirmation of geology, qualification of the variation and risk grade of each zone using borehole information.

c) The further adaption of the grade of risk by reviewing damage records and property utilisation.

The proportional contribution made by each of the final risk classifications will be determined by the intensity of the investigation (e.g., number of boreholes) and the applicability of the factor (e.g., are there any structures?).

Comments:

a) This system appears to be designed for application in the context of a non-dewatering scenario. Van Rooy (1984) researched and developed the system with respect to a non-dewatered area south of Pretoria. Consequently the only agency considered to be operative in the creation of instability events is ingress water. No reference is made to the process of dewatering or other relevant disturbing agencies, water level fluctuation, gravity and ground vibrations.

b) Van Rooy (1984) contends that zones on infrared imagery with either dark grey or black tone should be assigned high to very high risk characterisations. He maintains that these zones represent areas of poor drainage. This interpretation may not be entirely correct. A moist clay (e.g., residual clay on an intrusive) which may serve as an aquitard, may be present in the upper profile giving rise to a cool spot due to dark signature of the moist clay.

This aquitard would enhance the stability, in fact warranting a low risk characterisation.

Such information must, therefore, be treated with great circumspection. The provision of rigid guide-lines equating risk with tone may lead to poor interpretation by the inexperienced.

c) Gravity is a valuable tool utilised to formulate an impression of the bedrock topography on a site. This information is vital in evaluating the stability of an area within the context of a dewatering scenario. Unfortunately this system fails to embrace the influence of the process of watertable drawdown and there is no dewatering scenario in this system. The bedrock gradient is relevant but of less importance in the case of a non-dewatering scenario. Schoning (1990), after concluding a study in an area south of Pretoria, has indicated that there is no preferential occurrence of sinkholes on any particular gravity anomaly. This research essentially contradicts the assertion made by Van Rooy (1984).

d) In the classification of borehole information, Van Rooy (1984) has followed the practice of other authors, such as Weaver (1979), in attaching only a negative connotation to "wad". Van Rooy's entire system appears to be structured around "wad" with emphasis being placed on "depth to wad, thickness of wad, characteristics of wad, material above and below the wad". The detailed comments made in this regard with respect to Weaver's X-Factor analysis are relevant here.

e) The classification utilising damage to structures must be applied with discretion. A lack of damage does not necessarily imply that the site is stable. Many crucial interrelated factors play a role; such as, the age of services, quality of services and township design etc.

f) Van Rooy (1984) fails to address the dewatering scenario. The risk of doline formation and sinkhole formation is not evaluated in this context.

A site may, in fact, be characterised as reflecting a low risk of sinkhole formation, due to ingress water but a high risk of doline formation, due to dewatering. This risk characterisation effectively precludes urban development.

3.6 A Classification system by Stephan (1975)

Stephan (1975) proposed a classification system based on applying "weighted" code numbers to various components of the dolomitic profile in order to evaluate the stability of a site. The implementation of this system requires that a standard code number is assigned to each horizon in the dolomite according to its probable stability. The suggested code numbers are as follows:

Code	Number
No sample return above solid rock	5
Wad	4
Wad and little chert	3,5
Wad and chert	3
Chert and wad	2,5
Chert and little wad	2
No sample return in solid dolomite	3
Leached dolomite	2
Unweathered dolomite	1
Terra rosa	1,5
Cemented chert in terra rosa	1,5
Chert, weathered chert and chert breccia	1
Shale, sandstone, quartzite, intrusive	-4
Weathered shale, weathered intrusive	0

Ten stability code numbers are clarified as following:

- Code Number 5: No sample retrieval above solid dolomite. This manifestation suggests two geological conditions:

a) A void.
b) A zone of poor, highly compressible material which cannot be retrieved due to air loss.

Code Number 5 therefore depicts the poorest conditions.

- Code Number 4: The wad-chert horizon.

In-situ wad is a highly compressible, loose material characterised by;

a) its mineralogy.
b) spongy structure.
c) very low density.

These characteristics, it is argued, support the assumption that unconsolidated wad can only exist in protected conditions. The implication is that unconsolidated wad occurs where the dolomite interface is characterised by extensive pinnacle development or where chert layers afford protection either by absorbing or bearing overburden pressure. Where overburden pressure is exerted on the wad above the water table, consolidation and densification of the soil material will occur. (Stephan (1975) as reported by Van Rooy (1984).

- Code Number 3: No sample retrieval in solid dolomite.

According to Stephan (1975) failure to retrieve sample in solid dolomite indicates the presence of a void. The overlying dolomite would have to bridge this void providing the degree of joining in the dolomite is adequate. This void can serve as a reservoir for downward moving residual products of the dolomite.

- Code Number 2: Leached dolomite (and dolomite residuum).

Stephan (1975) maintained that a definition of leached dolomite can include dolomite and dolomite residu (e.g., terra rosa and wad).

Terra rosa is defined a red brown residual soil which occurs as overburden over limestone bedrock. This soil is usually cohesive and has a higher density than wad.

- Code Number 1: Unweathered dolomite, chert, weathered chert.

These rocks constitute the most stable conditions in the dolomite succession. The degree of pinnacle development is unknown and sinkhole development cannot be discounted.

- Code Number -4: Shale, quartzite, sandstone and intrusives.

It is assumed that these rock types have a stabilising influence on the dolomite profile. Questions that arise are:

i) What thickness of these materials must be present to in fact have a stabilising effect?.

ii) What is the maximum depth at which these rock types can occur and still have a stabilising effect?

iii) What is the stabilising role of these rock types in the weathered state?.

Application of the code numbers:

Each code number is multiplied by the thickness in metres of the particular layer in the profile. A depth correction is also applied because the influence of a poor layer at 20 m is not the same as that of poor layer at 5 m depth. Stephan (1975) proposed a 1 per cent reduction in the code number for each 5 metre increment of depth.

If stable materials such as shale, quartzite, diabase and syenite are present, the code number - 4 is multiplied by the total thickness of the manifestation of these rock types without implementing either any reduction or correction factor. In this case the only imposed limitations are as follows:

a) the total thickness of these horizons must exceed 8 metres.

b) the upper contact of these stabilising horizons must be at a depth less than 30 m from ground surface.

If these horizons are less than 8 m thick then is assumed that the influence on stability is negligeable and a code number of 0 is assigned. If these horizons are deeper than 30 metres Stephan (1975) believes that it is possible that small sinkholes can form.

The summation of the calculated stability of the various horizons gives the total calculated stability of each profile. These calculated values can be divided into three classes namely;

<0	Area suitable.
0-40	Area suitable for development provided that water precautionary measures are applied.
>40	Area unsuitable for development.

Comment:

This system grossly simplifies the complex dolomite environment. Stephan (1975) proposes that a simple weighting system be utilised to represent the material's geotechnical character. The rigid system results in a layer of a particular description being assigned a specific value irrespective of its position and interaction with other layers in a certain geological setting. The arrangement and thickness of various layers in a profile are as important as other factors such as the water level.

The system does not include any reference or make any allowance for the context in which the evaluation is being affected, either a dewatering or non-dewatering situation. Any layer of soil material will behave differently depending on whether it is located either above or below the water level or whether the water table is being drawn down through the layer. The assigning of a single value, positive or negative, is, therefore, incorrect.

The following fallacies must be considered:

(i) The term "wad" is simply utilised to describe a range of soil materials ranging from clays through silts to sands. These materials will have differing geotechnical characteristics and will behave accordingly. Consequently assigning a single poor weighting value to a range of soil materials is depriving the engineering geologist of latitude to assess its actual behaviourial characteristics within the geological setting.

(ii) Chert in terra rosa, chert, weathered chert and chert breccia tend to be viewed positively by the author of this system. Experience and statistics tend to indicate that these materials may, in fact, be extremely problematical in certain geological settings. A preponderance of sinkholes tend to occur in the chert rich formations particularly where gap graded materials are present. Schoning (1990) confirms this contention in an analysis of the occurrence of sinkholes in a non-dewatered environment.

(iii) "Unweathered dolomite" is viewed positively. The setting is however, crucial. Receptacles must be assumed to be present in the dolomite as no technique exists to detect either their presence or absence. Shallow bedrock (<3 m) implies that receptacles may be located close to ground surface.

The interface between bedrock and the thin soil cover provide potential flow paths for ingress water. Consequently such areas are normally viewed as reflecting a high risk of sinkhole formation.

The points discussed above merely serve to emphasize that in the evaluation of dolomite sites generalisations must be avoided. The application of rigid systems will result in gross over-simplification. On each site, each layer in each borehole must be evaluated in the context of the unique geological setting of the site. No two sites will be the same.

Stephan (1975) indicates that the upper contact of the stabilising horizons must be at a depth of less than 30 m from ground surface. If deeper than 30 metres, Stephan (1975) believed that small sinkholes could form. Although the basic concept is supported, very large sinkholes could, in fact, develop if a material with extensive disseminated receptacle development were to occur overlying the stabilising horizon which is at 30 m depth.

3.7 Evaluation of potential instability in Karoo outliers (Jones, 1986).

Several proposals, such as those of Venter (1981), de Beer (1981) and Wagener (1983) have been offered to classify the instability potential of dolomitic sites. It is considered, however, that in the case of Karoo outliers, the inter-related and interdependent influences of lithology, geological structure and hydrology must be taken into account. Consequently Jones (1986) proposes that the potential instability in Karoo outliers may be evaluated by:

a) Ranking the physical or engineering characteristics of individual lithological units constituting a geological profile according to their potential for instability.

b) Expressing the instability potential of a specific geological profile by weighing the engineering or physical characteristics of each lithological unit it contains, according to its apparent thickness.

c) Predicting the impact which subsurface water elevation may have on the geological succession.

d) Taking cognizance of the dolomitic bedrock configuration and the presence of any cavities.

e) Instability potential of lithological units: The author suggests that the instability potential of either a rock or subsoil is a function of its compressibility, erodibility and inverse of its tensile strength or cohesion.

In the case of unconsolidated subsoils, for example, their compressibility may be quantified in terms of the compression index (Cc) and the co-efficient of consolidation (Cv) as determined by laboratory tests. In the case of chert gravels and weathered Karoo sedimentary rocks, however, the above-mentioned tests are ineffectual. Wrench (1984) suggested that plate tests on pedogenic gravels, dolomitic rubble and terrace gravels show relationships between Young's modulus, plate bearing capacity and consistency and that these relationships provide "... initial estimates of compressibility and bearing capacity during foundation investigation in gravels ..." As far as intact rocks are concerned, Hobbs (in Jones 1986) also suggested that Young's modulus may be applied to determine potential instability. In the case of rock masses, however, cognisance must be taken of joints and fractures which may also contribute to ground instability potentials. Coon and Merrit (1970) advocate the use of fracture frequency (i.e. the number of fractures per metre) to quantify rock quality in terms of a mass factor "j". The erodibility of residual soils and soft rocks is a more difficult parameter to quantify. It is suggested, however, that any attempt to evaluate potential erodibility should take into account grading (percentage passing 0,075 mm) and permeability as influencing factors.

As far as the tensile strength of residual materials or soft rocks is concerned, the cohesion value "C" is considered a meaningful measure in the case of unconsolidated materials.

For sedimentary rock, however, the tensile strength' of rock material adjusted for its "j" factor, may be used as an evaluating parameter. It is suggested that the parameters of compressibility, erodibility and inverse of tensile strength can be given numerical index values to quantify their instability potential. Low numerical values would indicate low compressibility, low erodability and high tensile strength or cohesion characteristics whereas high index values would indicate the inverse. The instability ranking of a specific subsoil or stratum ' ind/L' could be derived from the formula:

$$ind/L = f(a,b,c)$$

In the above formula, 'a' 'b' and 'c' represent the instability index values given to compressibility erodibility and tensile strength/weakness respectively.

Jones (1986) emphasised that without explicit information, the instability promoting status of 'a', 'b' and 'c' in the above formula cannot be related. It is essential, therefore, that if valid ranking index values are to be obtained, detailed analysis should be made of each physical characteristic for every individual material in a large number of instability occurrences.

f) Instability potential of a specific geological profile:

Jones (1986) proposed that the instability potential of a specific geological profile 'RF' may be compiled by weighting the instability index value (ind/L) of each individual material in the succession according to its thickness or apparent thickness. The equation for such an evaluation would, therefore be:

In the above equation 'ind/L' and 't' represents the instability ranking index value of an individual material and its thickness respectively, whereas 'T' represents the total thickness of all the materials in a specific geological succession.

It would be noted that the thickness attained by materials in a specific succession may be influenced by the degree of slumping to which they have been subjected to during pre-Pleiststocene planation.

g) Evaluation of risk at a specific site: Obviously an 'RF' value based on the geotechnical characteristics of stratum, as described above, can only apply to a particular geological profile at a single point (e.g., a borehole) since it does not take cognizance of other influencing factors; namely lithological sequence, subsurface water and the configuration of the dolomitic bedrock (Jones 1986).

i) Lithological sequence:

Jones (1986) indicates that the method of compiling the 'RF' value as described above does not take into account the influence of the lithological order prevalent in the geological succession. Thus, as a simple example, it would be unrealistic to give a geological profile where 15 m of unconsolidated wad overlies 30 m of intrusive or mudstone the same 'Rf' value to a succession where 30 m of mudstone overlies 15 m of unconsolidated wad.

The author emphasises therefore, that 'Rf' values should be carefully scrutinised and modified where necessary by discerning earth scientists and engineers.

ii) Subsurface water:

Probably the most important influence for promoting instability in a geological profile is the movement of subsurface water. For example, the movement of water through a profile comprising a considerable thickness of unconsolidated wad would be more hazardous than similar movement through Karoo mudstones, siltstones and tillites. Consequently Jones (1986) argues that in the compilation of an instability risk hazard evaluation for a site, a hydrological factor rated with numerical values to indicate its contribution to instability, must be applied to the 'Rf' value of each individual profile existing in the area.

iii) Configuration of the dolomitic bedrock:

The configuration of the dolomitic bedrock considerably influences the potential instability of a Karoo outlier. A severe palaeo-karst subsurface configuration with short span distances between steep-sided pinnacles, is conducive to potential sinkhole development providing the infilling materials possess high erodibility and poor tensile strength (Jennings, Brink, Louw and Gowan, 1965). Conversely, a gently undulating dolomitic bedrock profile, in which the span between the shallow sloped abutments is too great to permit the formation of an arch will produce conditions favouring either differential surface settlement or doline development. Jones (1986) supported the method for classifying bedrock configuration proposed by Venter (1981) whereby the parameters of abutment slope- gradient, height and width are applied.

iv) Cavities and voids:

Venter (1981) proposed that a percentage factor should be applied for the presence of cavities in the dolomitic bedrock. Similar cognizance should be taken of voids occurring in either the residual subsoils or Karoo sedimentary rocks with particular reference to their spatial dimensions and depth from surface (Jones 1986).

The compilation of a potential instability risk evaluation "RH" at any specific point or site can therefore, be derived by the following formula:

$$RH = f\ (Rf,\ Rs,\ Rh,\ Rd,\ Rv)$$

In the above formula, Rf represents the instability potential of a given geological profile as already discussed, whereas Rs, Rh, Rd and Rv refer to the influences of the lithological sequence, subsurface water movements, the nature of the dolomitic bedrock configuration and the frequency of voids /cavities respectively; each being given numerical values which increase with rising instability potential.

Provided sufficient borehole information is available regarding geological profiles, geophysical and borehole data in respect of the dolomitic bedrock information and piezometers, strategically installed to monitor subsurface water movements, RH isopleth maps can be prepared to evaluate a site.

Comment:

Only two comments are made with respect to this system.

(i) The system is well developed but only applies to a very specific geological setting.

(ii) Many of the factors considered may be too difficult to determine e.g., receptacles. No technique exists to determine either the extent of void development, depth of occurrence or spatial dimensions.

3.8 Summarised conclusions of this review of existing classification systems and various investigation reports

A number of concerns are noted in the field of stability evaluation after a review of approximately 500 stability investigation reports and the specific assessment of the evaluation systems discussed above, namely:

i) Generally there appears to be a lack of either sufficient explanation or detailing in stability evaluation reports of how an area has been characterised as displaying a certain risk of sinkholes or dolines developing. There is thus no record of the frame work in which deductions were made and conclusions drawn. It is essential that such information be documented in the investigation report.

ii) There is a lack of standard risk categories and there is no standard scale nor classes of sinkhole sizes. The terms small and large sinkholes have different meanings to different investigators.

iii) There is a lack of adequate terminology, accepted by the entire fraternity, to denote various facets and features in the profile that may influence the stability evaluation.

iv) These classification systems tend to provide a rigid framework or set of rules guiding the assignment of numbers to parameters. These numbers are manipulated to culminate in a numerical expression of the evaluation. Kleywegt (1987) stated of these systems "that while they are useful in guiding an investigation by highlighting that what needs to be established, they are generally site specific and I fear the likelihood that they be applied universally or mechanically by inexperienced operators in situations where they do not apply". Schoning and A'Bear (1987) concluded that "classification systems need to be flexible and capable of being tailored to suit individual sites".

Given the present state of technology applied to the information gathering process during the execution of stability evaluations, it is clear that the stability assessment procedure cannot be viewed as a precise science. It is essentially therefore that an evaluation system is developed that embodies this limitation in a manner that is not misleading with respect to the scientific validity of the conclusions. Consequently it is proposed that systems based on mathematical formulae are avoided at present. Rather, use should be made of a general set of factors, utilised as a check-list, defining a deductive process and culminating in a stability characterisation. Each parameter would be interpreted according to individual professional experience. Consequently, it is firmly believed that this proposed check-list will permit latitude for individual professional expression. The intention is to guide and discipline discussion and motivation in a systematic and thorough manner during the evaluation and reporting process. In essence, a system is being sought that is similar in objectives to the standard profiling procedures

(Jennings et al 1975). All those factors believed to be important by Venter (1981), Weaver (1979), Von Rooy (1984), Wagener (1982), De Beer (1981) and Jones (1986) should be embraced.

4. THE METHOD OF SCENARIO SUPPOSITION FOR STABILITY EVALUATION

In response to the identified need for a standardised, functional methodology, Buttrick (1988) proposed a single framework of reference for the evaluation of stability. This proposal was developed after reviewing the mechanisms of sinkhole formation, existing classification systems, investigation procedures and stability investigation reports. In addition, the framework embraces the experience derived from deliberations with consultants, field visits to sites under investigation, viewing large numbers of sinkholes/subsidences, inspecting caves and the execution of stability investigations.

This approach is entitled the "Method of scenario supposition." This term is used to describe the methodology adopted in order to determine the stability characterisation of sites. The characterisation of a site necessitates hypothesising the probable consequences of man's activities on the site during the lifetime of the development. The potential behaviour of the virgin tract of land must be reviewed within the context of various scenario's (e.g. within the context of a dewatering scenario). The basic supposition in this evaluation process is the selection of the potentially applicable scenario's. The scenario provides the framework within which the evaluation procedure may proceed.

The individual boreholes representing subsurface conditions on the site can only be evaluated and characterised if abstractly subjected to the activity of an assumed mobilising agency within the context of the selected scenario.

4.1 Factors* for characterisation of the risk of sinkhole formation

The successful execution of the stability evaluation process is dependent on the correct identification of the factors that play a role in the process of sinkhole and doline formation. Essentially, it must be established whether or not the conditions inherent in the profile indicate a susceptibility to sinkhole /doline formation. If the profile is assessed as being susceptible, it is important to express this susceptibility in terms of the risk of a certain event occurring.

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* Factor is used in the context "circumstances, fact or influence contributing to a result".

The postulated mechanism of sinkhole formation, as discussed previously, involve differing prerequisites and agencies necessitating that the evaluation process encapsulate a broader based analysis of the possible contributing factors. Current knowledge of the mechanisms of sinkhole formation is fraught with uncertainty. At this stage, use should be made of a generalised and simple set of factors to express the risk of a certain size event occurring in a particular profile.

A generalised list and definitions of these proposed evaluation factors, which essentially reviews those conditions in a profile which are indicative of the potential susceptibility to sinkhole formation, is given below. These factors will also give an indication of the likely maximum size of sinkhole.

4.2 Definition of factors for the characterisation of the risk of sinkhole formation.

The proposed factors are defined below. These factors can readily be identified during the stability investigation.

i) Receptacles.

Either the receptacles or disseminated receptacles occurring within the bedrock or within the overburden and can receive mobilised materials (Plates 5 and 6).

These receptacles may occur either as small disseminated and interconnected openings in the overburden or as substantial openings (caves) particularly in the bedrock.

An extensive network of fissures should be viewed as potential receivers and storers of material and not just as conduits.

ii) Mobilising agency.

Mobilising agencies include ingress water, ground vibrations, water level drawdown and any activity or process which induces mobilisation

Plate 5: Gap graded chert rubble and fines.

Plate 6: Disseminated receptacles, jointed chert and potential flow paths

of the material within the blanketing layer.

The evaluation process can only be undertaken by assuming that a mobilising agency is acting on the materials within the blanketing layer. The potential behaviour of the material under the influence of this agency or agencies can be predicted. Example: If it is assumed that the profile will be subjected to a mobilising agency in the form of ingress water, then the potential susceptibility to erosion of the materials within the blanketing layer must be assessed.

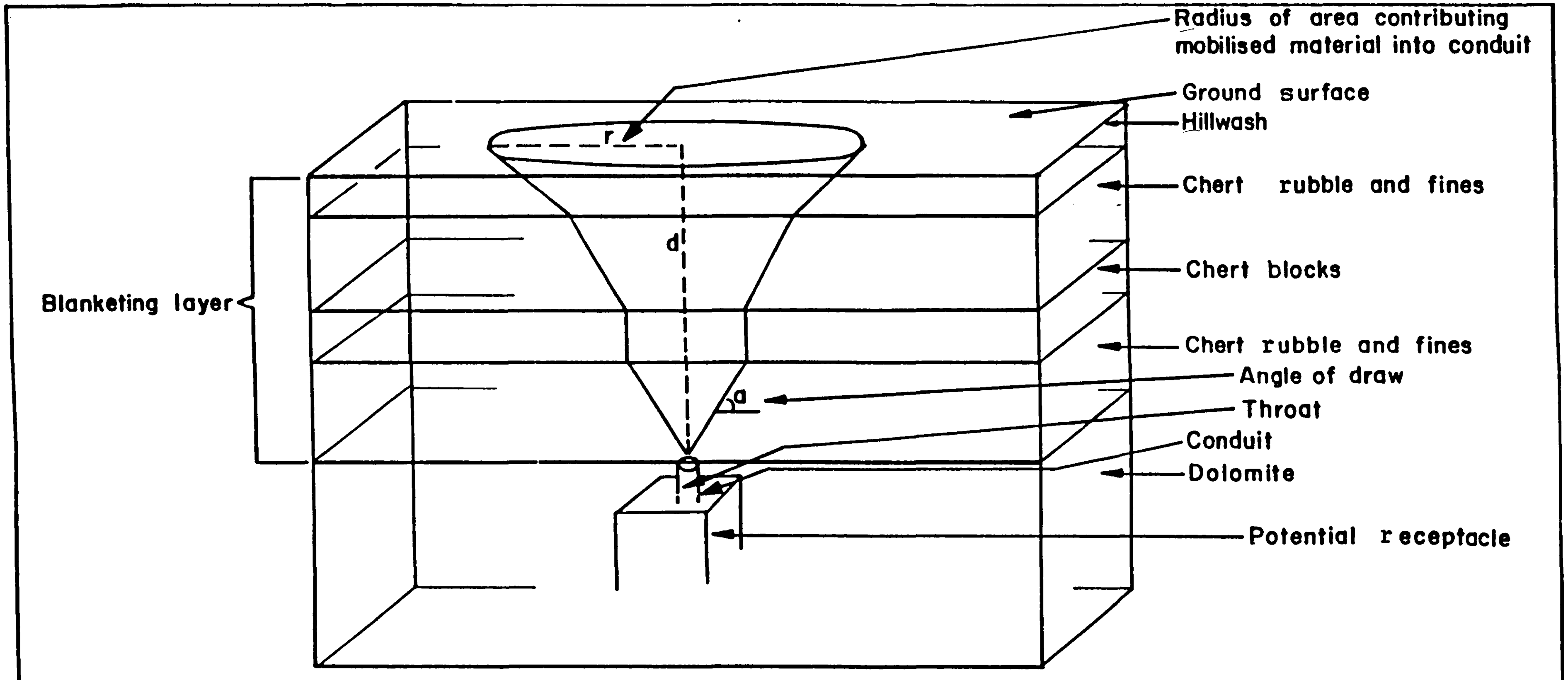
iii) Blanketing layer

Overburden refers to any loose, unconsolidated material which rests upon solid rock (Whitten and Brooks, 1972). The overburden is thus the dolomite residuum and other materials found overlying the dolomite bedrock and occurring between the ground surface and the dolomite interface. The term "blanketing layer" is, however, suggested to denote that component of the overburden which overlies the potential receptacles (Figure 16).

The nature of the material constituting this component of the profile is crucial to the advancement, retardation or prevention of the process of sinkhole/ subsidence formation.

iv) Maximum potential sinkhole development space

The "maximum potential sinkhole development space" is a simplified estimation of the maximum size sinkhole that can be expected to develop in a particular profile: providing that available space is fully exploited by a mobilising agency (Figure 17). The potential development space (pds) is associated with either a receptacle or disseminated receptacles and depends on the following factors:



r = Radius of surface manifestation of potential development space (PDS)

Figure 16: Maximum potential development space.

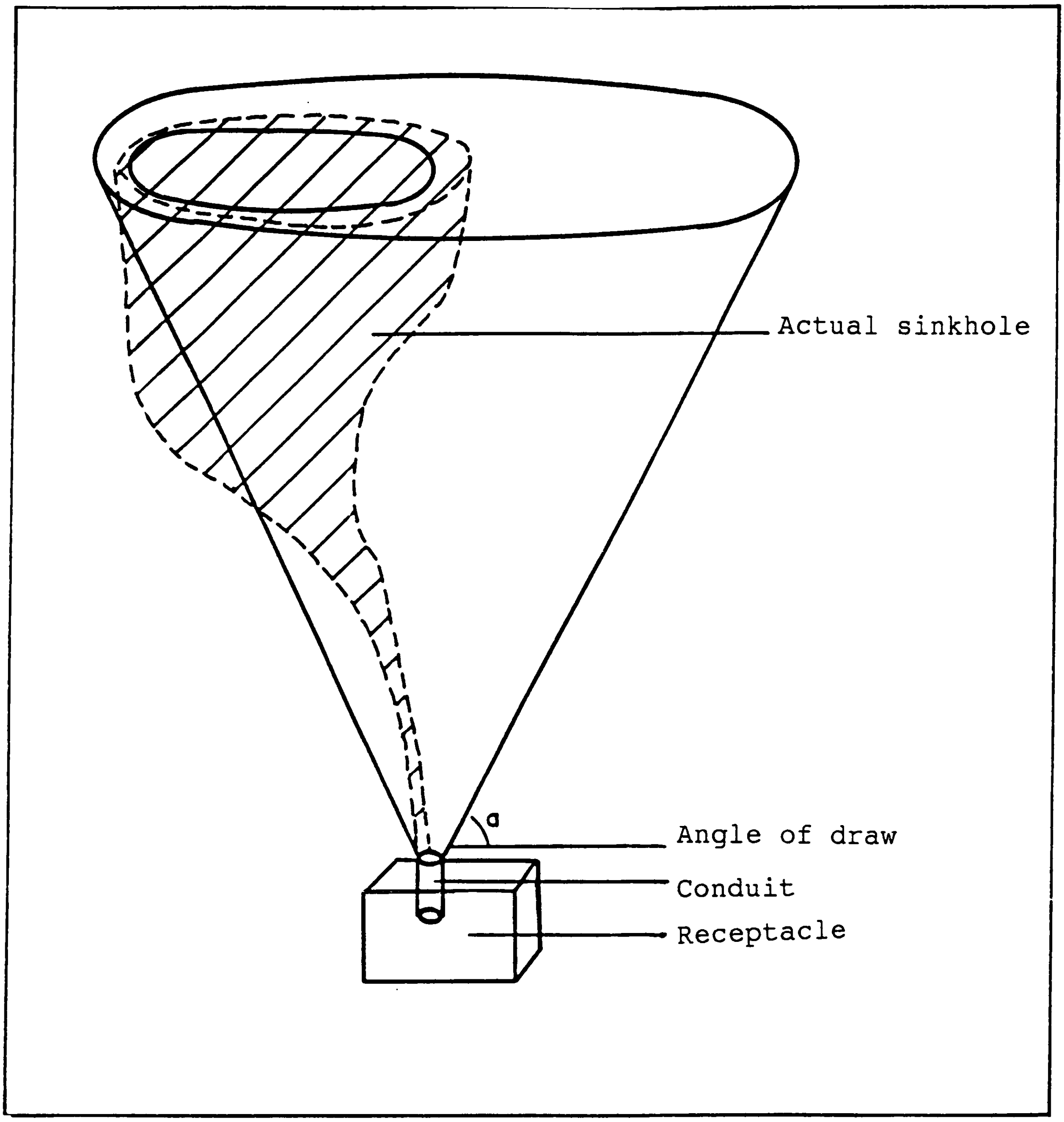


Figure 17: Maximum potential development space is not fully utilised.

a) estimated depth below ground surface to the potential throat of either the receptacle or disseminated receptacles, (i.e the thickness of the blanketing layer).

b) estimated "angle of draw" in the various horizons in the blanketing layer. The "angle of draw" in a material defines the angle of a metastable slope to which a particular mobilising agency will work in that material. Simply, the "angle of draw" scribes a cone. The material within the cone can potentially be mobilised, moving or being drawn into the conduit at the base of the cone. Typical angles of draw may be as follows:

- Chert	90 degrees
- Alternating chert and silty clay (wad)	80-90 degrees
- Shale	90 degrees
- clayey silt (wad)	45 to 60 degrees
- silty clay (wad)	45 to 75 degrees
- chert rubble with clayey silt	45 to 90 degrees

These figures are merely cited as examples of the range of values for the angle of draw. The values are dependent on local conditions, observation of actual sinkhole sidewalls in the immediate area, if available, and more importantly, geotechnical information gathered during the field investigation. Rigid values cannot be prescribed for a number of reasons:

- Use of pre-determined values would defeat the objective of evaluating local conditions.

- To provide values for the angle of draw would defeat the entire exercise of encouraging professional judgement and it is essential that liability rests in the hands of the engineering geologist undertaking the investigation.

- Soil materials are highly variable in character. For example in a medium of chert rubble and fines, where the rubble is predominant, the geotechnical characteristics are totally different to where the fines component constitutes the larger percentage of the sample.

c) the thickness of the various horizons constituting the blanketing layer. Figure 16 displays this concept diagrammatically. The depth to the potential receptacle is obtained from borehole information and the radius of the potential development space on surface is obtained by a simplified diagrammatic construction. The "angle of draw" of the various materials and the depth of the receptacle is used to project and estimate the radius.

Realisation of the full sinkhole size may include a catastrophic event when it "daylights", followed by the growth of the feature due to slip failures and ravelling along the sidewalls. This process will continue until a metastable state is achieved The sinkhole could potentially grow until it fully utilises the limits defined by the potential development space (Figure 18 and 19).

Thus, for each receptacle there is a "potential development space" which may be fully realised or exploited, creating the maximum size sinkhole, provided that:

A) The receptacle is large enough to accommodate all mobilised material from within the "development space"

B) The materials constituting the blanketing layer can be mobilised

C) An adequate and sustained mobilising agency is present to mobilise all the material.

In reality, the receptacle may be too small to accommodate the mobilised material and, hence, the maximum potential development space may not be fully utilised (Figure 18). In such an instance, where a profile is characterised by receptacles of an inadequate volume, the maximum potential development space and typical maximum size sinkhole will not be synonymous.

The Star Wednesday July 4 1990 3

NEWS

Talking point . . . Katlehong residents gather around the sinkhole that has opened up in this East Rand township. ● Picture by Sean Woods.

Katlehong sinkhole keeps getting bigger

By Adam Gordon

A sinkhole which first appeared in the East Rand township of Katlehong on Saturday has grown to the size of a small swimming pool and may threaten residents' houses nearby.

The hole is in the street which runs between the areas of Motloung and Moshoeshoe. It is about 6 m long, 2 m wide and 6 m deep. The area has been cordoned off by Katlehong street committee members.

Ben Malika of the Katlehong Civic Association said the hole had doubled in size on Sunday and kept getting bigger. When it first appeared it was about the size of a bath.

Another resident, Simon Matsamane, said many thousands of litres of water had flowed out of a water pipe which had broken when the hole appeared. He thinks the water could affect the foundations of nearby houses.

Katlehong's mayor, Gideon Molotsi, said there have been various other sinkholes in Katlehong in the past.

The town clerk, Fanie Mare, said the holes had been caused by water running out of underground water cavities during the dry season.

He said the hole would be filled as soon as consulting engineers and geologists had been consulted.

Ben Malika of the Katlehong Civic Association said the hole had doubled in size on Sunday and kept getting bigger. When it first appeared it was about the size of a bath.

Figure 18: Growth of a sinkhole.

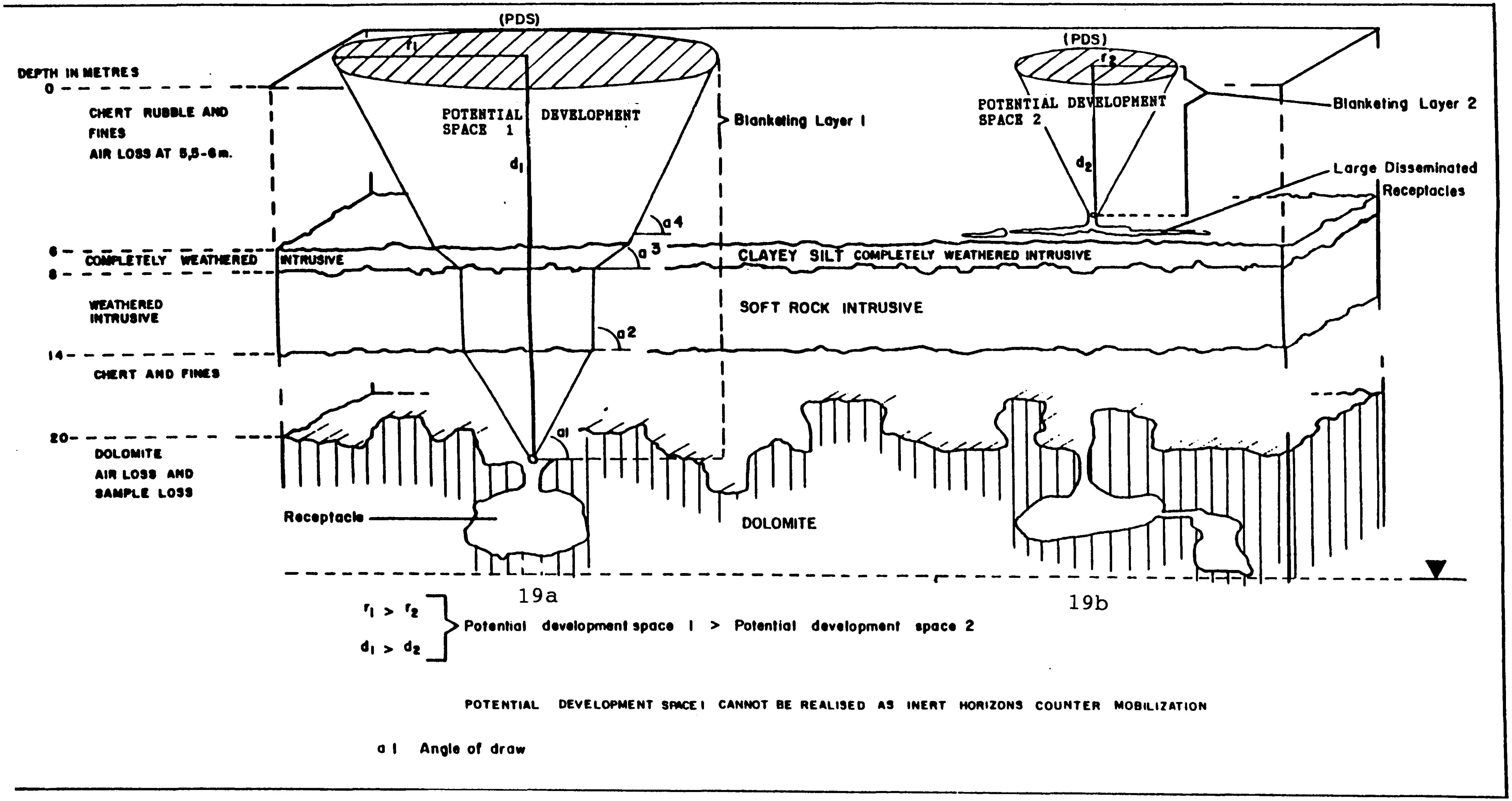


Figure 19: The influence of horizons with a low mobilisation potential on the maximum Potential Development Space (PDS).

The maximum size sinkhole will be smaller than the potential development space. As there is no efficient technique available at present to ascertain the volume of receptacles it is assumed that receptacles of adequate volume are present. If our technology permitted prediction of receptacle volume, the likelihood of the exploitation of the full potential development space could be expressed. The risk of realising the maximum potential development space would depend on the susceptibility of the materials of the blanketing layer to mobilisation, the volume of the receptacle and sustained action of the mobilising agency. The dolomite residuum is not a homogeneous mass. Various mixtures of coarse and fine material will influence the angle of repose resulting in smaller size features forming. If the matrix is a finer material, its properties may dominate and if the coarse material is abundant, its properties may prevail. Obviously hard rock bands and masses will also confine development.

It must be emphasised that the "potential sinkhole development space" may represent an extremely conservative assessment of the space available in the profile for the development of the maximum potential size sinkhole.

v) Development space and sinkholes.

Table 12 contains proposals of broad categories of "potential development space" and hence the associated scale of potential maximum size sinkholes.

vi) Assessment of the mobilisation potential of materials in the blanketing layer.

Under the influence of a mobilising agency, it is the materials that occurring within the blanketing layer, which determine the potential susceptibility of the development space to

Table 12: A suggested scale of sinkhole sizes

	DIMENSIONS* (metres)	
MAXIMUM POTENTIAL DEVELOPMENT SPACE	MAXIMUM DIAMETER OF SURFACE MANIFESATATION	SUGGESTED TERMINOLOGY
Small Potential Development Space	< 2	Small sinkhole
Medium Potential Development Space	2 - 5	Medium size sinkhole
Large Potential Development Space	5 - 10	Large sinkholes
Very large Potential Development Space	> 10	Very large sinkholes *

* Dimensions are based on scrutiny of existing sinkholes. Very large sinkholes refer to those notorious features such as the Blyvooruitzicht, West Driefontein Venterspost and Jachtfontein sinkholes and a number of palaeosinkholes.

exploitation and mobilisation. This susceptibility should be expressed in terms of the risk of mobilisation. The materials may reflect a low, medium or a high risk of mobilisation under the influence of a particular mobilisation agency. If the materials within the blanketing layer resist the activities of the mobilising agency, the risk of mobilisation will be low.

A shallow water table, widespread and continuous Karoo shales or intrusive materials may serve to enhance the stability of a profile. A shallow watertable will, for example, serve to protect the surface profile and materials within the blanketing layer and, hence, the "development space" from the erosive activity of ingress water.

The different mobilisation risk categories are characterised as follows:

- Low risk of mobilisation of blanketing layer materials:

  The profile displays no voids. No airloss or sample loss is recorded during drilling operations. Either a very shallow water table or a substantial horizon of materials with a low potential susceptibility to mobilisation may be present within the blanketing layer, (e.g., continuous either intrusive features or shale material).

- Medium risk of mobilisation of blanketing layer materials:

  This type of profile is characterised by an absence of a substantial "protective" horizon and a blanketing layer of materials potentially susceptible to mobilisation by extraneous mobilisation agencies. The water table is below the blanketing layer.

- High risk of mobilisation of blanketing layer materials:

  The blanketing layer of the high risk

profile reflects a great susceptibility to mobilisation. A void may be present within the potential development space indicating that the process of sinkhole formation has already been affected. Boreholes may register large cavities, sample loss, air loss, etc. The watertable is below the blanketing layer.

Figure 19 indicates a profile with a deep groundwater level situated within the bedrock. The blanketing layer and hence the potential "development space" is fully exposed to the potential activities of extraneous mobilising agencies. This figure depicts a significant layer of material with a low mobilisation potential.

This horizon acts either as an aquitard or aquiclude preventing mobilisation and movement of materials into the receptacle. The material within the "development space" is thus protected from the mobilisation agency (Figure 19). Figure 19b depicts the same profile as in figure 19a, but investigation reveals the presence of potential disseminated receptacles above the horizon displaying the low mobilisation potential. A smaller potential development space is thus available for exploitation by a mobilising agency.

4.3 Evaluation parameters for the characterisation of the risk of doline formation.

A general list of evaluation parameters which essentially reviews those conditions in a profile which are indicative of the potential susceptibility to doline formation and the scale, is given below:

- Mobilisation agency.
- Nature of blanketing layer.
- Mobilisation potential of blanketing layer.
- Lateral extent.

4.3.1 Mobilisation agency

The evaluation process can only be completed by assuming that a mobilising agency **is** operative. If it is likely that dewatering of the local dolomite aquifer, on which the site is located, will occur during the lifetime of the development then the dewatering scenario must be reviewed.

4.3.2 Nature of the blanketing layer.

- Thickness of the soil material (depth to bedrock).
- Depth of the original watertable.
- Nature of the soil material above the watertable (i.e., type of soil and geotechnical characteristics).
- Nature of the soil material below the watertable (i.e., type of soil and geotechnical characteristics).

4.3.3 Mobilisation potential.

The influence of the mobilisation agency on the profile material is determined by the following:

- Thickness of the overburden
- Depth of the original watertable
- Thickness of the soil material above the watertable.
- Thickness of the soil material below the watertable.
- Nature of the soil material above the watertable.
- Nature of the soil material below the watertable.

The susceptibility of the soil material to mobilisation i.e., consolidation settlement under the influence of the mobilising agency (watertable drawdown) may be characterised as follows:

a) Low risk of doline formation

i) Watertable in the bedrock

ii) Watertable in soil material with geotechnical characteristics reflecting a low susceptibility to consolidation settlement i.e., possessing a high density, low void ratio, low Cc compression index) and Cv (consolidation coefficient) values. For example, watertable drawdown through Karoo shale draped directly over dolomite.

b) Medium/High risk of doline formation

Watertable above bedrock in soil material with low dry density values, high void ratio, high Cc (compression index) and high Cv (consolidation coefficient) values. The potential for dramatic ground settlement is reflected in the properties of residual dolomite soils, namely wad and ferroan soils. Typically these silts and clays display a great susceptibility to consolidation settlement of significant magnitudes.

Note : Any positive influence of a bulking factor in overlying materials is accepted as being too difficult to predict within the ambit of most stability investigations.

4.4 Implementation of the method of scenario supposition

Geophysical surveys and/or relevant remote sensing techniques and field information are used to subdivide a site into potential (karst) morphological zones (Steps 1 and 2 Figure 20).

Boreholes are then placed to characterise these zones. The normal procedure would be to characterise each borehole using the method of scenario supposition (Step 4, Figure 20). The scenario/s selected as prevalent on the site dictates which mobilising agency/cies will be assumed to be operative. The various evaluation factors can then be assessed within the framework of the designated scenario. This assessment would include determining the potential development space and evaluating the potential for mobilisation of the materials within the blanketing layer under the influence of the particular mobilising agency. In considering the aspect of potential sinkhole formation for example the factors would be reviewed as follows:

Figure 20: Method of Scenario Supposition

Step 1:

Field scouting and desk study of site

Step 2:

Preliminary zoning utilizing tools such as API,* Geophysics

Step 3:

Preliminary boreholes to characterise "preliminary" zonation

Step 4:

Characterisation process. (Scenario Supposition) INDIVIDUAL BOREHOLE PROFILES ARE REVIEWED within the context of the selected scenario/s

EVALUATION FACTORS	
SINKHOLE FORMATION	**DOLINE FORMATION**
Mobilisation agency/agencies. receptacle development. Potential development space (i.e.potential sinkhole size) Nature of blanketing layer/s. Mobilisation potential of blanketing layer/s.	Mobilising agency. Nature of blanketing layer/s. Mobilisation potential. Lateral extent

Step 5:

Pooling of individual borehole characterisations and amending of preliminary zoning taking historical information into account.

Step 6:

FINALISED RISK ZONATION CHARACTERISED IN TERMS OF A CERTAIN RISK OF CERTAIN SIZED FEATURES FORMING

Step 7:

SELECTION OF APPROPRIATE DEVELOPMENT TYPE AND PRECAUTIONARY MEASURES

Step 8:

IMPLEMENTATION OF APPROPRIATE DEVELOPMENT DESIGN AND PRECAUTIONARY MEASURES

Step 9:

VIGILANCE AND MAINTENANCE

* API - Air photo interpretation

i) Receptacle development.

The presence of either major receptacles or disseminated receptacles to receive mobilised materials is first considered. Any suppositions made should be elaborated on in the reporting stage of an investigation. For example, are receptacles assumed to be present although not encountered?. A crucial matter to be evaluated from available information is the depth of the potential receptacles. Are there particular horizons occurring above the dolomite bedrock that may be characterised by disseminated receptacles?

ii) Mobilising agency/agencies.

In the evaluation and reporting procedure it is important to clearly indicate which particular external mobilising agencies or combination of agencies the blanketing layer will be subjected to during the lifetime of the development. Motivation must be provided for assumptions made in the deductive process. The selected scenario/s determine the agencies utilised and the course of the investigation.

iii) Potential development space.

The following step in the evaluation process is to define the "maximum potential sinkhole, development space" within the blanketing layer. Alternatively discuss the most likely scale of events. Elaborate on and motivate the selected procedure of determining the potential scale of catastrophic events.

iv) Nature of blanketing layer/s.

Discuss the geological and geotechnical characteristics of the material constituting the blanketing layer/s with particular attention to the grading and internal drainage characteristics.

v) Mobilising potential of blanketing layer.

Consider the susceptibility of the material constituting the blanketing layer to mobilisation. The susceptibility to consolidation and subsurface erosion, including piping erosion, should be carefully argued considering aspects such as the internal drainage characteristics.

The characterisations of the individual boreholes within a potential zone are then pooled (Step 5, Figure 20). If several boreholes confirm a particular characterisation that zone will be defined accordingly. If there are marked deviations, the zoning must be modified by the creation of separate zones, always erring in the favour of a conservative assessment.

5. RISK CHARACTERISATION AND RECOMMENDED TYPE OF URBAN DEVELOPMENT

5.1 Proposed zoning system

An engineering geological stability investigation culminates in the characterisation of an area proposed for development as reflecting, firstly a certain risk of certain size sinkhole developing, and secondly a certain risk of doline formation. The characterisation of the site renders pertinent information for design purposes.

Urban development, as previously discussed, normally results in a disturbance of the metastable conditions prevalent in the dolomite environment. Consequently the basic design of the township is a key element in the overall strategy to minimise the impact of the proposed development on the environment. (The particular type of development selected in relation to the risk characterisation is critical to the safe and successful long term viability of a project.) For example: The placement of a high density "site and service" scheme on an area characterised as displaying a high risk of a medium size sinkhole developing must not be allowed. Such development is less controlled, services of an inferior quality may be utilised and there may not be the necessary control on surface drainage. If a catastrophic event was to occur, the high population concentration dramatically increases the risk of many people losing their lives. An area with such a risk characterisation would be better utilised for commercial or light industrial development. More expensive design solutions can be employed to reduce the likelihood of aggravating the metastable state.

Buttrick (1988) proposed the use of a zoning system relating the risk characterisation of an area and certain suitable or appropriate types of development. Table 13 denotes these suggested suitable types of development as related to the risk characterisation. Development design is based on the most conservative assessment for an area, that is, on the risk of the most catastrophic event occurring.

The recommendations are a logical progression of measures ranging from:

- limited restriction on the type of residential development, provided that certain precautions are taken in the design and maintenance of services through;..

Table 13: Examples of risk characterisation and appropriate development.

CHARACTERISATION

RISK OF DOLINE AND A SPECIFIED SIZE SINKHOLE FORMING

RISK CLASS	SMALL SINKHOLE	MEDIUM SIZE SINKHOLE	LARGE SINKHOLE	VERY LARGE SINKHOLE	RISK OF DOLINE FORMATION	RECOMMENDED TYPE OF DEVELOPMENT
Class I	Low	Low	Low	Low	Low	Any density and type of residential, light industrial and commercial development provided that appropriate water precautionary measures are applied. Other factors affecting economic viability such as excavatability, problem soils etc., must be evaluated .
Class II	Medium	Low	Low	Low	Low	Residential development including high density, low cost housing (affordable housing). Also suitable for commercial or light industrial development.
Class III	High	Low	Low	Low	Low	Selected residential development. High density housing only with engineering & expensive precautionary measures. Acceptable for lower density residential development, multistoried complexes commercial & light industrial development. No informal settlements
Class IV	Low - Medium	Medium	Low	Low	Low - Medium	As above but with exceptionally stringent precautionary measures, and design criteria. No site and service schemes. Also consider highrise residential development

Table 13: (Continued) Examples of risk characterisation and appropriate development.

CHARACTERISATION

RISK OF DOLINE AND A SPECIFIED SIZE SINKHOLE FORMING

RISK CLASS	SMALL SINKHOLE	MEDIUM SIZE SINKHOLE	LARGE SINKHOLE	VERY LARGE SINKHOLE	RISK OF DOLINE FORMATION	RECOMMENDED TYPE OF DEVELOPMENT
Class V	Low - Medium	Low	Low	Low	Low-Medium *NDS	Highrise residential structures, gentleman's estates, commercial or light industrial development. Expensive foundation designs may be necessary. Sealing surfaces/earth mattresses water services in sleeves or in ducts etc.
Class VI	High	High	Medium	Low	Low - High *NDS	Gentleman's estates (stands 4 000 square metres), commercial or light industrial (dry) development.
Class VII	High	High	High	Medium	Medium - High *NDS	No residential development. Special types of commercial or light industrial (dry) development only (e.g. bus or trucking depots, coalyards, parking areas). All surfaces sealed. Suitable for parkland.
Class VIII	High	Medium	High	High	Medium - High *NDS or DS	No development, nature reserves or parkland.

*NDS = Non-dewatering scenario
*DS = Dewatering scenario

- restrictions that affect both the density of development and the type of development. For example; making provision for structures where the additional costs of special foundations and precautions can be afforded, to

- recommendations that land allocation be restricted to open areas or special parks.

The basic philosophy of this zoning system is therefore, that with increasing risk of more catastrophic events occurring, so the density of development should decrease and construction costs increase.

The table does not deal with all the possible combinations of risks and events but does indicate development type as related to a trend of "increasing risk of increasingly catastrophic events". It must be borne in mind that the denoted risk is a reflection of the "inherent" geotechnical characteristics of the subsurface profile and remains so irrespective of the land use. Essentially, a potential behaviourial characteristic is being assigned to the subsurface profile. It is being suggested that if the profile is exposed to the activities of a certain mobilising agency, it will be expected to behave in the denoted manner.

The risk characterisation can only be determined if the profile is subject to "abuse". If the land has a "high risk of large sinkholes forming" it retains that characterisation irrespective of the development type. What does change is the probability of evoking an event by abusing the surface area. If the "high risk" land is used as a park the probability of evoking an event will be less than if it were utilised for high density residential, development. Consequently in order to reduce the probability of evoking an event, it is necessary that the development selected for any area is appropriate in relation to the risk.

5.2 Motivation for the recommending certain appropriate types of development in relation to the risk characterisation.

The relationship between risk of ground movement and type of development described in Table 13 is motivated by simple logic and the use of available statistics. Analysis of events in existing developed areas on dolomite reveal the following:

(i) Man's influence invoked events:

Ground movement events, either catastrophic or gradual, can be related to man's activities. Research by Schoning (1990) has revealed that of 380 sinkholes that have formed in a study area south of Pretoria, 96% were artificially induced due to man's influence or activities. In an earlier study, the causes of 101 sinkholes formed in an area in the north of Verwoerdburg and south of Pretoria were analysed by Roux (1984). It was found that all 101 incidences were artificially induced by man's activities. A random sample of 31 sinkholes and the causes are given in Table 14. All were attributable to surface water ingress.

(ii) Low cost housing can only be placed on the most suitable dolomitic land:

The facts given in (i) above cause concern when it is realised that the most rapid development on dolomite is in the field of "low cost, high density housing" and more particularly "site and service schemes".

(iii) Increasing numbers of ground movement events are associated with increasing densities of development:

As an illustration of this statement and the concepts being conveyed in Table 13, consider an area that is characterised as displaying a medium risk of large sinkholes forming. The mobilising agency is ingress water. Consider three possible types of development on this land:

a) Gentlemen's estate:

- Advantages:

The size of these properties are normally in excess of 4 000 square metres in extent, usually containing one house, with approximately six

Table 14: Randomly selected ground movement events and their potential causes

Sinkhole /Doline	Location	Cause
Sinkhole	Duiker Rd, Clayville	Leaking sewer
Doline	Kameeldoring St, Valhalla	Undetermined
Doline	Fiord St, Valhalla	Old french drain
Doline	Shirley St, Valhalla	Undetermined
Doline	Alanic St, Valhalla	Old french drain
Doline	Aero St, Valhalla	Old french drain
Doline	Falen St, Valhalla	Leaking swimming pool
Doline	Shirley St, Valhalla	Leaking water pipe
Doline	Hugo St, Valhalla	Old french drain
Doline	Oscar St, Valhalla	Old french drain
Doline	Alanic St, Valhalla	Leaking water pipe
Doline	Sesmylspuit, Erasmia	Leaking water main
Doline	School, Verwoerdburg	Poor surface drainage
Doline	Research Inst, Irene	Leaking water pipe
Doline	Saphire St, Valhalla	Old french drain
Doline	Erasmia	Stormwater drain
Doline	Shirley St, Valhalla	Leaking swimming pool
Doline	Lambert St, Valhalla	Leaking water pipe?
Doline	Lotter St, Valhalla	Leaking water pipe?
Doline	Atlas St, Valhalla	Leaking water pipe
Doline	Bruarfess St, Valhalla	Leaking water pipe
Doline	Glen Lauristen	Leaking water pipe
Doline	Braurfess St, Valhalla	Poor surface drainage
Sinkhole	Lyttleton	Poor surface drainage
Sinkhole	Olive Rd, Valhalla	Poor surface drainage
Sinkhole	STO Sportsfield	Leaking water pipe
Sinkhole	Buchanan St, Valhalla	Leaking water pipe
Sinkhole	Valhalla	Leaking water pipe
Sinkhole	Waterkloof	Poor drainage
Sinkhole	Hoewe St, Lyttleton	Poor drainage
Sinkhole	Cuprene St, Laudium	Poor drainage
Sinkhole	Sports Centre, Laudium	Leaking water pipe
Sinkhole	Atteridgeville	Leak. pipe/poor drain.
Sinkhole	Ashwood Dr, Clubview	Leaking water pipe
Sinkhole	Verwoerdburg	Storm water drain
Sinkhole	Erasmia	Storm water system
Sinkhole	Cradock St, Lyttelton	Leaking water pipe?
Sinkhole	Steenbok,Monument Park	Leaking water pipe
Sinkhole	Swartkop 356 JR	Stormwater pipe
Sinkhole	Lyttelton, Irene-Pta Rd	Poor drainage
Sinkhole	Bergen St, Valhalla	Leaking sewer
Sinkhole	Andrew Rd, Valhalla	Leaking water pipe
Sinkhole	Imatre St, Valhalla	Leaking water pipe
Sinkhole	Park, Valhalla	Undetermined
Sinkhole	Valhalla	Leaking sewer

inhabitants per stand. The structures may be placed on the most suitable locality on the 4000 square metres. There is a low density of waterbearing services. In addition, precautions such as placing services in ducts or sleeves for 10 m beyond the household structure can be considered.

- Disadvantages:

Gentleman's estates preclude maximum utilisation of available land in an area zoned for residential development and hence diminishes the likelihood of lower unit costs. Gentleman's estates are usually about 4 000 square metres in size. Thus a stand of 4 000 metres replaces a potential 10 to 13 stands. Space is obviously taken up by access roads. Overcrowding often occurs. Consequently 380 to 494 people, may occupy 4 000 square metres in an informal settlement compared with the figure of 6 people in the case of a Gentlemen's Estate.

A much higher density of waterbearing services must be installed to serve 10 to 13 structures. There is a greater volume of water in the sewerage system. There is also a greater negative environmental impact particularly to the soil profile due to trenching, blasting and other means of excavation.

The greater extent and overloading of waterbearing services, combined with the fact that there is an almost 100 per cent occupational coverage of the township surface, sets the scene for a grave disaster. Experience indicates that the services will deteriorate with time with a concomitant increase of population density.

There is a risk that uncontrolled unstructured settlements will develop on these properties with increasing risks of substantial loss of life.

b) Commercial/light industrial development:

- Advantages:

Stands may be of any size. A figure of 4 000 square metres will be considered. If the site is used for warehousing, a large percentage of the surface area may be covered by structures. There would be a low density of waterbearing services and these could be placed in ducts or sleeves in the vicinity of the structures. More expensive foundation designs may be considered. Surface areas around structures may be sealed. The cost of these materials and precautionary measures would be realistic with respect to the overall financial investment in the project.

- Disadvantages:

Such developments cannot simply be placed within an area zoned for residential development. Only a certain percentage of the available land can be utilised for this type of development.

The particular type of development selected in relation to the risk is critical in ensuring the safe and successful long-term viability of a project. The arguments presented above indicate that to utilise inappropriate township design in relation to characterised risk, would be extremely negligent.

The crux of the matter is that as the density of development increases, so the density of waterbearing services and the number and volume of water leakages increase. Table 15 indicates that in areas of similar risk characterisation an increasing number of ground movement events are induced, as development density increases. This fact is obviously related to an increasing density of waterbearing services in association with an increasing urban density resulting in a greater frequency of service failures.

Table 15: Comparison of instability events as recorded in different communities

	LYTTELTON (TOWN)	IRENE
Stands	1 000 - 1 500 sq.m	800 - 1 500 sq.m
Mobilising agency	Ingress water	Ingress water
Risk characterisation	Medium risk of large sinkholes	Medium risk of large sinkholes
Sinkholes	30 (1970 - 1981) *	3 (1970 - 1981) *
	LYTTELTON AGRICULTURAL HOLDINGS	VALHALLA
Stands	> 4 000 sq.m	800 - 1 500 sq.m
Mobilising agency	Ingress water	Ingress water
Risk characterisation	Medium risk	Medium Risk
Sinkholes	2 sinkholes #	33 sinkholes/ 27 subsidences

* Water bearing services are of similar age

\# Statistics until 1984. Further sinkholes and subsidences have occurred in the Lyttelton Agricultural Holdings as the character of the area has changed. The old holdings are presently being sub-divided with more intensive residential and commercial development occuring.

5.3 Design Recommendations

The general precautionary measures for all sites located on dolomitic land are given in section 5.3.1. These measures apply to all the risk classes (i.e. I to VIII, Table 13).

Specific additional precautionary measures are also given for the particular risk characterisations (i.e. risk classes I to VIII).

5.3.1 General precautionary measures for all sites on dolomite including Class I to VIII sites.

The general precautionary measures listed below apply to all developments on dolomitic land. Specific additional measures with respect to each class of site are given in subsection 5.3.2.

1. No accumulation of surface water is to be permitted and the entire development must be properly drained (Plate 7 and 8).

2. Water-borne sewerage reticulation must be installed. French drains are unacceptable.

3. All trenches and excavation works must be properly backfilled and compacted according to specifications given in subclause 5.2.4 of SABS 1200 DA.

4. All ponds and water courses must be rendered impervious by suitable design using, for example concrete or plastic sheeting.

5. In order to deal with rain water run off from the roofs of structures the following is recommended (Plate 9):

    a) If guttering is required by the local authority, then the down pipes should discharge into a lined or precast furrow. This furrow should discharge the water at least 1,5 m away from the house.

    b) If no guttering is to be utilised then it is recommended that an 1,5 m sealed surface be cast along those walls of the structure where water will be discharged from the roof. Water will cascade off the sloping roof onto the slab and be distributed away from the foundations (Plate 10 and 11).

Plate 7: Poor drainage manifest along roadside.

Plate 8: Poor drainage on portion of township.

Plate 9: Poor water management around house foundation.

Plate 10: Poor drainage around new house. Note erosion adjacent to foundation.

Plate 11: Poorly located, unlined drainage channel immediately adjacent to sewerage line. Note ground movement.

6. All storm water sewerage and water pipes and channels must be watertight. All laid drainage and sewerage pipes should be tested for leakage using the air test (see NBRI Info. Sheet X/BOU 2-34) on installation, and thereafter at least once every 2 years.

7. Chapter II in "A Technical Guide to Good House Construction" NBRI of the CSIR (July 1984) should be consulted concerning the potential corrosion of pipes.

8. Water pipes entering buildings should be fitted either with flexible couplings or kinked with a Z to allow opportunity for relative movement.

9. When utilising polyethylene and unplasticized polyvinyl chloride (UPVC) piping it should be noted that the use of compression type joints is preferred. The use of heat fusion, glue fusion or screw threading requires great skill for installation and may pull apart with very little differential movement.

10. No trees should be planted over the line of water bearing services.

11. Careful consideration of permission to sink boreholes as a control on dewatering. If the watertable is above bedrock, a blanket ban on exploitation of the groundwater should be imposed. Approval should be subject to an evaluation of the implications by an engineering geologist.

12. Ensure that roadways are in fact placed below site level so as to facilitate drainage (Plate 7).

5.3.2 Special design recommendations for dolomitic land with different risk characterisations.

5.3.2.1 Class I land

Class I land includes those areas characterised as reflecting a low risk of doline and sinkhole formation (see Table 13).

Class I sites may be utilised for any density and type of residential, light industrial and commercial development provided that appropriate design and precautionary measures are implemented.

These sites should preferably be utilised for residential development and the higher risk sites reserved for commercial/industrial development.

Factors, other than the dolomitic stability, such as excavatability and problem soils, which may have an effect on the economic viability of a development, must be evaluated.

If the land of this class is to be utilised for site and service schemes, the following aspects require consideration:

a) The low risk areas should preferably be constituted by the following characteristics:

   i) Karoo material draped directly over dolomite.

   ii) Substantial thickness of Karoo or intrusive material occurring at shallow depth in relation to overall depth to bedrock. Dewatering must not be a potential mobilising agency.

   iii) Confident prediction of the lateral continuity and distribution of these materials (i.e. lateral boundaries).

b) A detailed sanitation plan should be drawn up for the development according to the local geological setting and engineering geological characteristics. Note that blasting during service installation may trigger ground movement events.

c) Roads need not necessarily be tarred but should be graded. Longitudinal slopes down unlined roads must be so designed as to prevent excessive storm-flow velocities developing. Such flow results in detrimental erosional scour.

It can be argued that because of light traffic and possible limitations in applied maintenance, basic access streets should be designed primarily to withstand environmental deterioration. Consequently, maintenance of drainage channels is more important than grading unsurfaced streets. Obviously design should be such that intensive types of maintenance are emphasised.

Depending on local, engineering geological and environmental constraints, this land can be considered for the location of grave yards and solid waste disposal sites.

5.3.2.2 Class II land.

Class II land includes areas characterised as reflecting:

- Medium risk of small sinkholes.
- Low risk of all other size sinkholes forming.
- Low risk of doline formation.

Class II sites can be utilised for residential development, including high density low cost housing affordable housing), commercial or light industrial development.

The general precautionary measures listed in section 5.3.1 apply to all developments on land with this stability characterisation. Specific additional measures are given below for low cost, high density housing projects.

- Bulk services should be placed either in road reserves or in servitudes with a minimum 5 m width. Servitudes may be utilised either as parks or "bridle paths".

- A detailed sanitation plan must be drawn up for any low cost developments to ensure that the level of servicing is compatible with the local geological setting and engineering geological characteristics.

5.3.2.3 Class III land.

Class III land includes areas characterised as reflecting:

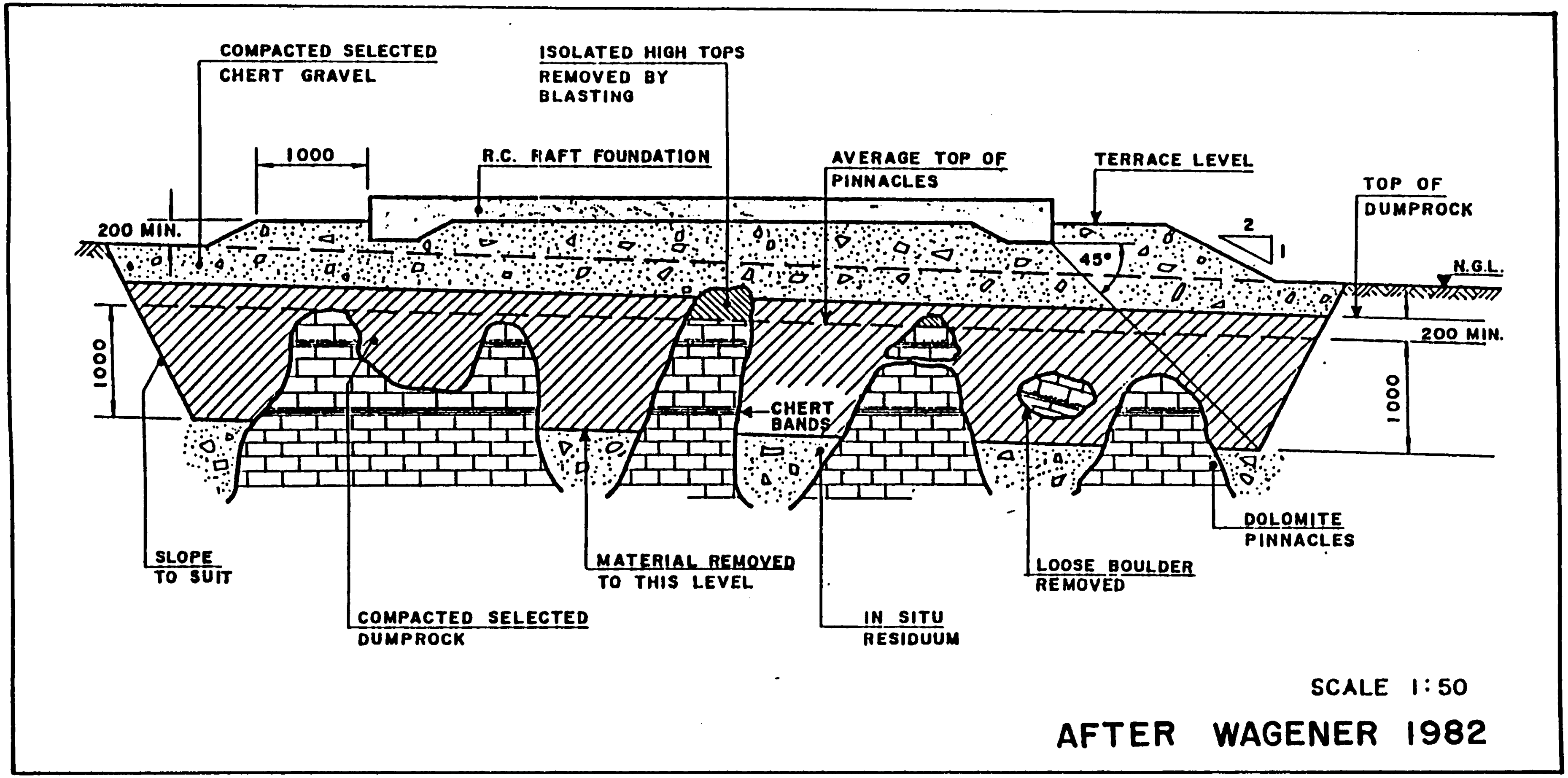
- High risk of small sinkholes forming.
- Low risk of all other size sinkholes forming.
- Low risk of doline formation.

Class III sites can be considered for selected residential development. High density housing projects can only be implemented on land with this risk characterisation if carefully engineered and expensive precautionary measures are implemented. These areas are acceptable for multistorey complexes, commercial and light industrial. Site and service schemes cannot be safely placed on this land.

The general precautionary measures listed in section 5.3.1 apply to all developments on dolomite land with this stability characterisation. Specific additional measures are given below:

- In the case of residential development it is recommended that structures be placed on earth mattresses. Areas displaying this risk characterisation are generally areas with shallow dolomitic bedrock. The earth mattress serves to ensure load distribution and to prevent water ingress. Mattresses are usually designed for individual homes in middle class developments. A continuous mattress can be considered for high density developments. A continuous mattress is emplaced in strips for block lengths and with widths exceeding the house footprint by at least 2 m (Figure 21 and 22).

  This exercise must be completed prior to



AFTER WAGENER 1982

Figure 21: Section through an earth mattress.

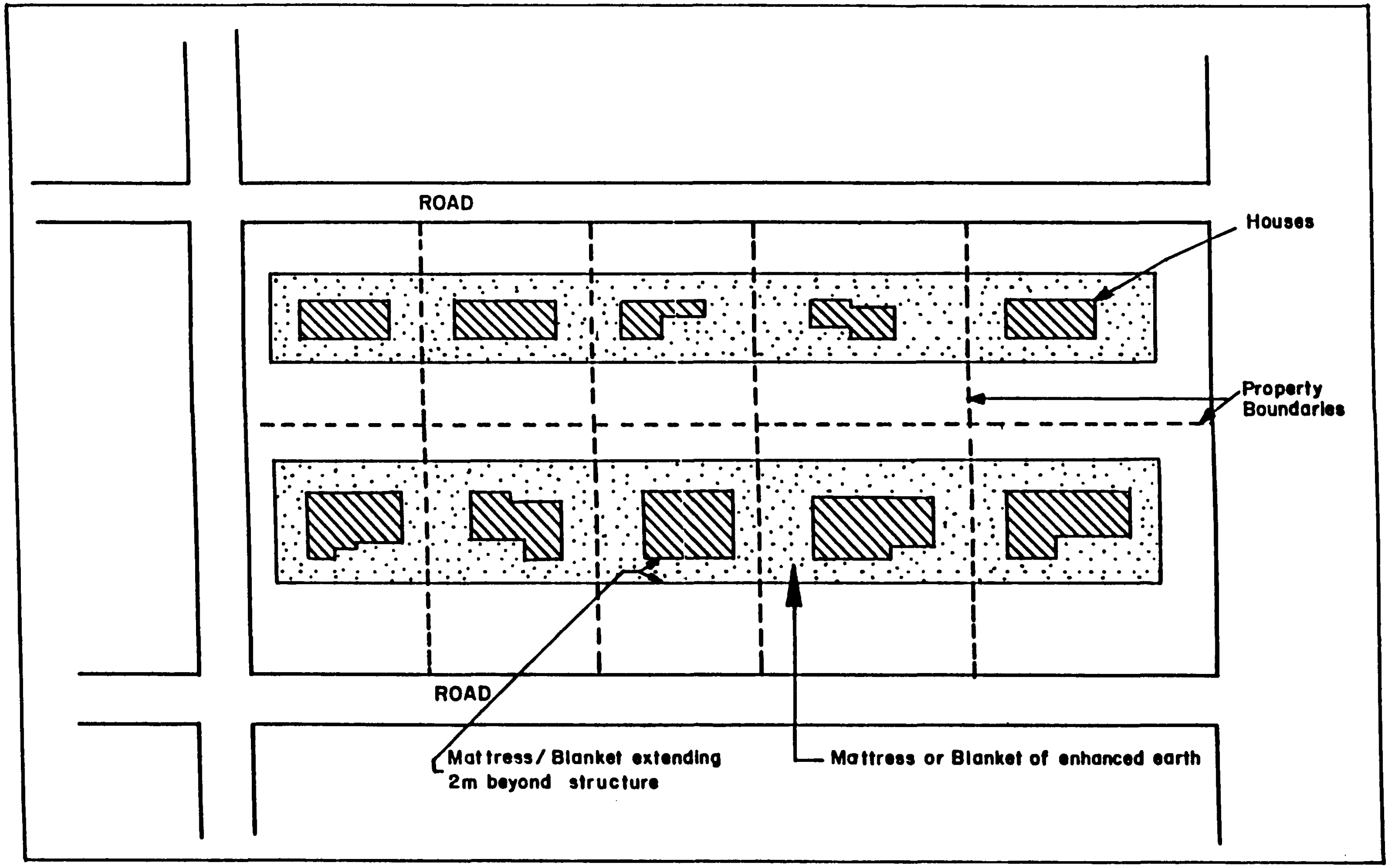


Figure 22: Mattress under several houses.

the installation of services. Water and sewer connections to households should be placed within the mattress. If the mattress is penetrated, wet services must be placed in sleeves for 5 m beyond the structure (Plate 12 to 16).

- Bulk services must be placed in road reserves or in servitudes of a minimum of 5 m width. Servitudes may be utilised as parks or " bridle paths".

- Water and sewer connections of every two units should be placed along their common property boundary. Shared sewer connections should be implemented if this system leads to a reduction in extent of service and minimises disturbance of the environment.

- Property and unit entrances should be placed at points furthest from the trenches of these water and sewer connections.

- Each stand should either have a rodding eye or some similar access to the sewer connection in addition to the inspection eyes (Figure 23).

- sewer and water reticulation systems should be placed either in road reserves or on pavements. If these reticulation systems are placed mid block, a building line restriction of a minimum width of 5 m must be imposed.

- Brick and precast concrete walls must be so designed as to provide drainage ports at ground level permitting passage of water.

Additional comments with respect to commercial/light industrial development

(i) Structures must be correctly and safely founded.

(ii) water bearing services should be placed either in the mattress, if utilised, or in sleeves, for a distance 5 m beyond the structure.

Plate 12: Earth mattress in preparation in an area of shallow dolomite.

Plate 13: Manholes giving access to sleeves of sleeved sewerage line.

Plate 14: Services exposed in large manhole. Note sleeves.

Plate 15: Sewerage line in sleeves exposed in manhole.

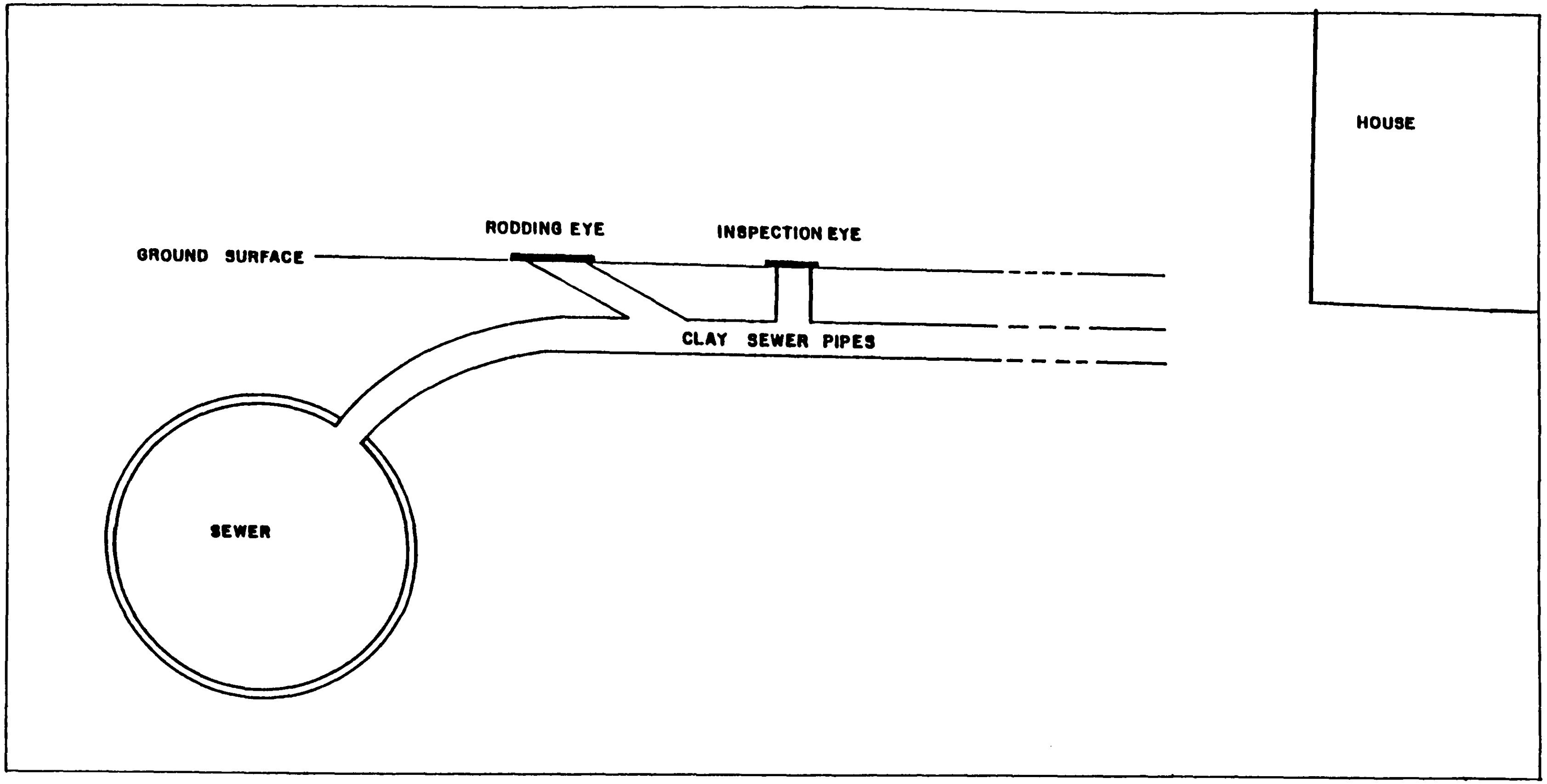


Figure 23: Rodding eye or some similar access to the sewer connection.

(iii) Surfaces should be sealed around and for at least 5 m beyond the structure.

(iv) Downpipes bearing accumulated roof water can be discharged either onto sealed surfaces to drain away from structures or into lined furrows and into roadways/stormwater systems.

Additional comments with respect to high rise structures. Multistorey structures, such as blocks of flats can be considered for placement on such sites provided that:

(i) These structures are correctly founded.

(ii) The principal waterbearing services are placed either in sleeves when within 5 m of the structure or where large movements of people occur (e.g., near the entrance to such structures).

(iii) The area immediately surrounding the building, to a distance 5m beyond the periphery of the building, is sealed with suitable paving or concrete.

(iv) Downpipes draining the roof of the structure discharge onto this sealed surface.

5.3.2.4 Class IV land

Class IV land is characterised as reflecting:

- A high or medium risk of small sinkholes.
- A medium risk of medium size sinkholes.
- A low to medium risk of doline formation in a non-dewatering scenario.

Class IV sites can be considered for selected residential development. High density housing only with engineering and stringent precautionary measures. Lower density residential development is preferable (i.e. stand>1000 m2). Isolated smaller housing units, such as those in low cost developments, are at risk due to their smaller size and the potential size of sinkholes. Units may topple or drop into sinkholes. These sites may also be utilised for multistorey structures, commercial and light industrial development.

- In the case of high density housing projects, it is suggested that the following precautions are considered in addition to those contained in 5.3.2.1:

  a) Structures be placed on a mattress of enhanced earth to reduce water ingress.

  b) Place services in sleeves for 5 m beyond structures if either the blanket is penetrated or if mattress is not used.

    - Place bulk services in road reserves or in servitudes of a minimum of 5m width. Servitudes may be utilised either as parks or " bridle paths".

    - Place water and sewer connections of every two units along their common property boundary. Shared sewer connections should be implemented if this arrangement leads to a reduction in the extent of service utilized and minimizes disturbance of the environment.

    - Place property and unit entrances at points furthest from the trenches of these water and sewer connections.

    - Each stand should have either a rodding eye or some similar access to the sewer connection in addition to the inspection eye.

    - Place the sewer and water reticulation systems either in road reserves or on pavements. If these reticulation systems are placed mid-block, a building line restriction of a minimum width of 5 m must be imposed.

    - Water pipes entering buildings should be kinked with a Z to allow for relative movement.

- Brick and precast concrete walls must be so designed as to provide drainage ports at ground level to permit the passage of water.

- Roadways must be sealed.

- Additional recommendations with respect to gentlemen's estates. Single housing units on a large stand (3 000 to 4 000 m2).

  i) Place structure on mattress of enhanced earth.

  ii) Place water bearing services either in the mattress or in sleeves for 5 m beyond the structures.

These expensive precautionary measures and foundation solutions are in a realistic balance with the overall investment in the development.

- Additional recommendations with respect to commercial/light industrial development.

  (i) Structures must be correctly and safely founded.

  (ii) Place water bearing services either in mattress if utilised or in sleeves for a distance 5 m beyond the structure.

  (iii) Seal surfaces around and for at least 5m beyond the structure.

  (iv) Downpipes bearing accumulated roof water can be discharged either onto sealed surfaces to drain away from structures or into lined furrows and into roadways / stormwater systems.

- Additional recommendations with respect to high risk structures.

Multistorey structures, such as blocks of flats can be considered for placement on such sites provided that:

(i) These structures are correctly founded and the structural integrity can be ensured.

(ii) The principal waterbearing services must be placed either in sleeves when within 5 m of the structure or where large movements of people occur (e.g., near the entrance to such structures).

(iii) The area immediately surrounding the building, to a distance 5m beyond the periphery of the building, should be sealed.

(iv) Downpipes draining the roof of the structure can discharge onto this sealed surface.

5.3.2.5 Class V land.

Class V land is characterised as reflecting;

- A high risk of small to medium size sinkholes forming.
- A low risk of larger sinkholes forming.
- A medium risk of doline formation (non-dewatering scenario).

A class V site can be utilised either for highrise residential structures, gentlemen's estates, commercial or light industrial development. Expensive foundation designs may be necessary. Sealing of surface around structures or the enhancement of subsurface conditions may be necessary. Examples: Creation of a compacted earth mattress extending beyond the limits of the structure. Mattress of in-situ excavated and recompacted material with small additional amounts of suitable soil to create a positive relief feature. Water-bearing services placed within the mattress, sleeves or in ducts. The purpose of the mattress is to retard water ingress. In addition to the precautionary measures stipulated in paragraph 5.3.2.1.:-

- Each stand should have a rodding eye or some similar access to the sewer connection in addition to the inspection eyes.

- Place the sewer and water reticulation systems in road reserves or on pavements. If these reticulation systems are placed mid-block a building line restriction of a minimum width of 5 m must be imposed.

- Place bulk services either in road reserves or in servitudes of a minimum of 5 m width. Servitudes may be utilised as parks or " bridle paths".

- Place water and sewer connections for every two stands along their common property boundary. Shared sewer connections should be implemented if this arrangement leads to a reduction in meterage of service utilized and minimizes the disturbance of the environment.

- Place property and unit entrances at points furthest from the trenches of these water and sewer connections.

- Expensive precautionary measures and foundation solutions are in a more realistic balance with the cost of development.

- Additional recommendations for commercial/light industrial development;

  (i) Structures must be correctly and safely founded and the structural integrity must be ensured.

  (ii) Place water bearing services either in blankets if utilised, or in sleeves for a distance 5m beyond the structure.

  (iii) Seal surfaces around and for at least 5m beyond the structure.

  (iv) Downpipes bearing accumulated roof water can be discharged onto sealed surfaces to drain away from structures or into lined furrows and into roadways/stormwater systems.

- Additional recommendations with respect to high risk structures. Multistorey structures, such as blocks of flats, can be considered for placement on such sites provided that:

  (i) These structures are correctly founded and the structural integrity can be ensured.

  (ii) The principal waterbearing services must be placed either in sleeves when within 5 m of the structure or where large movements of people occur (e.g., near the entrance to such structures).

  (iii) The area immediately surrounding the building, to a distance 5 m beyond the structure, must be sealed.

5.3.2.6 Class VI land.

Class VI sites are characterised as reflecting:

- A high risk of small to medium size sinkholes.
- A medium risk of large sinkholes.
- A medium to high risk of doline formation in a non-dewatering scenario.

Such sites may be used either for gentlemen's estates, commercial or light industrial development. Precautionary measures, as for Class V land, are applicable.

5.3.2.7 Class VII land

Class VII sites are characterised as reflecting;

- A high risk of small to large sinkholes forming.

- A medium risk of very large sinkholes forming.

- Low to medium risk of doline formation in a non-dewatering scenario.

No residential development should be allowed on class VI land. Only special types of either commercial or light industrial development (e.g. Bus/Trucking depots, coal yards). Such land is most suitable for parkland.

5.3.2.8 Class VIII land

Class VIII sites are characterised as reflecting;

- A high risk of all size sinkholes forming.
- A medium to high risk of doline formation in a non dewatering scenario or
- A medium to high risk of doline formation in a dewatering scenario.

No development should be allowed and the area can be utilised for parklands, nature reserves and similar uses.

6. SITE INVESTIGATIONS, REPORTING AND PROCEDURAL REQUIREMENTS

It is imperative, as the pressure for land to be made available for low cost housing on dolomite increases, that standards, prerequisites and precautionary measures are not abandoned or carelessly relaxed due to financial pressures. To the contrary, there must be increasing vigilance as the population density on dolomite increases. Safe, sensible and economical development will ensure the long term viability of these developments and the wellbeing of the populace.

The stability characterisation of a site permits appropriate development and the selection of pertinent precautionary measures. These factors are key elements in the overall strategy to minimise the impact of the proposed development on the metastable environment.

In order to competently advise the Provincial Secretary and local authorities on the risk characterisation of sites, safety and viability of developments, the following recommendations are made:

3.1 Reporting procedures for stability and foundation investigations *1

It is recommended that reporting procedures be standardised or at the very least that they should contain the information listed below.

The stability and shallow foundation investigation *2 report must

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Footnote:

*1 "Stability investigation" refers to the study of the engineering geological characteristics, of the dolomite rock and the blanketing materials, including soils and other materials such as Karoo rocks. This study may include reviewing the geotechnical characteristics of material and rocks to a depth of 100m. Particular attention is paid to the potential for sinkhole and doline formation with careful evaluation of the engineering geological characteristics, geohydrological information and other environmental factors.

*2 Shallow foundations investigations refer to the study of the superficial soil materials particularly the upper 3m mantling the site.

essentially be a concise, well documented record of the available information, procedures and methodology adopted and the conclusions and recommendations pertaining to a particular investigation. The document should clearly and unambiguously record the engineering geological evaluation procedure. There must be no uncertainty as to how the site was characterised. Many stability investigation reports simply detail the available information, present comment on the geology and leap to the conclusions and recommendations. Failure to detail the deductive procedure, in essence signifies a failure to competently conduct the investigation.

The discussion below embraces those topics regarded as essential in order to ensure a composite record of the investigation of a site. The intention of the discussion embraced in this section, is to provide a standardised guideline for the content of a stability investigations report.

Reports must detail the following information:

6.1.1 Introduction

The introduction should at least deal with the following aspects:

a) Terms of reference

Reference should be made to the basic information concerning the appointment and assigned task.

b) Objective of the investigation

The primary objectives of the investigation should be detailed. These objectives are, normally, to determine the nature and distribution of soils and rocks underlying the site and thereafter to:

- Comment on the general stability of the portions of the site underlain by dolomite in terms of the risk of sinkhole and doline formation,
- present general geotechnical information for site development works,
- present appropriate recommendations for township design

and precautionary measures.

c) Location of the site

Urban: Co-ordinates, preferably on a reproduced portion of a 1:50 000 topocadastral map . List the town or suburb name. If the suburb name is not yet available, use the farm name, number and portions or part portions.

Rural: Farm name, number and portions or part portions.

Many reports fail to give clear locality information and maps. It is imperative for data banking purposes that correct, detailed information is given. Unnecessary delays to the proclamation process may result as a consequence of either inadequate or poor locality description.

6.1.2 Available information

This section is utilised to briefly note those sources of information consulted during the investigation. This information includes sources such as topocadastral, geological, geophysical and geohydrological maps and reports, borehole data, aerial photographs etc.

In the case of reports, full references should be given while in the case of maps, the number and source should be given. The job, strip and photograph numbers should be given for aerial photographs which are used.

6.1.3 Procedure/content/scope of the investigation.

The methodology of the investigation should briefly be discussed with reference to:

a) The type of investigation (i.e. does it include both a stability and shallow foundation investigation). The shallow foundation investigation information is essential for a complete and competent evaluation of the stability to be made.

b) All the investigation techniques employed and benefits to be derived from utilisation of these techniques.

c) The monitoring techniques employed during the investigation (e.g. piezometers).

d) Explanation for the adoption of the techniques and procedures.

In addition an explanation should then be given as to how the positioning of the boreholes has been determined (e.g. with or without gravity information).

6.1.4 Description of the site

Discussion should include the following aspects:

a) Size.

b) Topography and, if possible, geomorphology.

c) Vegetation cover.

d) Past and present land use.

e) Hydrology and geohydrology.

6.1.5 Geology.

Discuss the following:

a) Regional geology (e.g Groups and Formations, intrusive rocks, structure, faults).

b) Site specific geology (i.e information derived from subsurface investigation). Comments on superficial cover materials (e.g hillwash and aeolian sands, etc.), residual soils, intrusions and the bedrock.

6.1.6 Geohydrology.

Discuss the following:

a) Regional geohydrology (i.e. compartment and sub-compartment etc).

b) Site geohydrology; elevations and contouring of water levels if feasible.

3.1.7 Stability evaluation

This section details the methodology adopted in affecting the stability characterisation of the site. The "deductive process", or framework of reference, utilised to characterize the site, must be elaborated on. The evaluation process essentially involves bringing together all the diverse information presented and listed in the previous sections of the report for analysis and characterisation.

Geophysical surveys, and/or relevant remote sensing techniques and field information are used to subdivide a site into potential karstological zones. Boreholes are usually placed to characterise these zones. The normal procedure would be to assess each borehole, characterising it as reflecting a certain risk of a certain size feature developing. This assessment would include determining the potential size feature that may form and evaluating the potential for mobilisation of the superficial materials overlying the receptacles under the influence of a particular mobilising agency.

The characterisations of the individual boreholes within a potential zone are pooled. If several boreholes confirm a particular characterisation, that zone will be defined accordingly. If there are marked deviations, the zoning must be modified with the creation of separate zones (Buttrick 1988).

The Unit for Applied Studies on Dolomite of the S.A Geological Survey has proposed the utilisation of a broad based approach to stability evaluation taking the parameters listed above into account. This suggested methodology, developed by Buttrick (1988), is used by the members of the unit and a number of consultants to characterise stability conditions on sites. A document detailing this methodology and suggested terminology is provided in Section 5.

6.1.8 Evaluation of the superficial founding material.

This section is devoted to the discussion of laboratory and field tests results. Shallow founding problems such as heavy clays, are identified based on laboratory and field information. The presentation of a "zones map" designating the distribution of the various problem soils is recommended.

6.1.9 Conclusions and Recommendations

The following aspects with respect to each zone should be discussed:-

- Dolomitic stability evaluation:

a) appropriate development in relation to the designated risk
b) appropriate precautionary measures and design criteria with respect to the selected type of development.

- Shallow founding problems: practical solutions.

6.1.10 References.

6.1.10.1 Appendices.

6.2 Approval of township design.

It is recommended that the engineering geologist responsible for the execution of the stability investigation, sign a statement indicating that he/she is satisfied that the design conforms to the stability characterisation and recommendations as detailed in the stability report. An example of such a declaration is given below:

THIS TO CERTIFY THAT THE TOWNSHIP LAYOUT ON THIS PLAN (NO. ....) IS IN ACCORDANCE WITH THE PROVISIONS AND RECOMMENDATIONS AS SET OUT IN THE ENGINEERING GEOLOGICAL REPORT NO.............. DATED ....

ENGINEERING GEOLOGIST/GEOTECHNICAL ENGINEER:

....(Sci Nat/Pr Eng.)

FIRM:...

....

DATE: ....

6.3 Approval of service design

It is recommended that the engineer/s, responsible for the design of the services, sign a statement or statements indicating that cognizance has been taken of the risk characterization and that the relevant recommendations. Furthermore, that precautionary measures, as detailed in the stability report, have been implemented in the design of the services.

7. APPLICATION OF THE METHOD OF SCENARIO SUPPOSITION

7.1 Introduction

This chapter illustrates the application of the method of scenario supposition in the context of both a non-dewatering and dewatering scenario. An area of high density development south of Pretoria, which has been subjected to detailed engineering geological investigation and has a well recorded history of ground movement events, constitutes an ideal study area for a non-dewatering scenario assessment. This assessment is discussed in great detail in the following pages. In the case of the dewatering scenario, a number of ground movement events from various dewatered compartments are analysed. The aim of these studies is to review and demonstrate the positive features and drawbacks of this methodology.

7.2 Review of the non-dewatering scenario.

7.2.1 General.

The area selected for the review of the non-dewatering scenario encompasses approximately 650 ha of land which is fairly well developed. The site is ideal for the purposes of this study for the following reasons:

(A) It encompasses two geological formations of the Chuniespoort Group, namely, the Lyttelton and Eccles Formations. Thus, both the chert-poor and chert rich formations are represented.

  (i) Lyttelton Formation: This formation, which is approximately 150m thick, is free of chert and consists of dolomite with large elongated stramatolitic mounds (SACS 1980). The dolomite tends to weather into sharp pinnacles.

  (ii) Eccles Formation: The Eccles Formation, which is approximately 380m thick, consists of dolomite and chert with the chert content increasing upward in the succession.

Overlying the dolomite of the Chuniespoort Group, infilling features (depressions) in the paleokarst surface are clays shales, sandstones, conglomerate and coal seams of the Ecca Group of the Karoo Sequence. A significant part of the site is underlain by a north-south orientated Karoo outlier (Figure 24).

Quaternary, aeolian sands, which are essentially reddish brown silty, fine sands, cover large parts of the site including the dolomites and the shales.

(B) The intensity of development varies from fallow, unutilised land through to intensely developed areas.

The intensely developed areas were principally established at least 30 to 40 years ago. Isolated, more recently developed structures are present in the development. Fallow undisturbed areas are very limited in extent and distribution. Man's influence has extended to the major part of the site.

(C) The site has experienced in excess of forty six incidences of ground movement including both gradual and catastrophic subsidence.

(D) Intensive engineering geological information is available, including gravity data, infrared linescan imagery, aerial photographic coverage and borehole data. A total of 95 reports cover various portions of the site. Approximately 70 test pits, 300 small diameter and 20 large diameter augerholes and in excess of 950 rotary percussion boreholes have been drilled.

(E) This area was utilised by Van Rooy (1984) for his comparative study of the MF - Classification system and some of the classification techniques discussed in Chapter 4.

The procedure adopted in this study is as follows:

(i) The available information has been studied and

LEGEND

●	Borehole position
r	Red soil
s	Shale
t	Sandstone
i	Intrusive
c	Chert
d	Dolomite
	Dolomite residuum

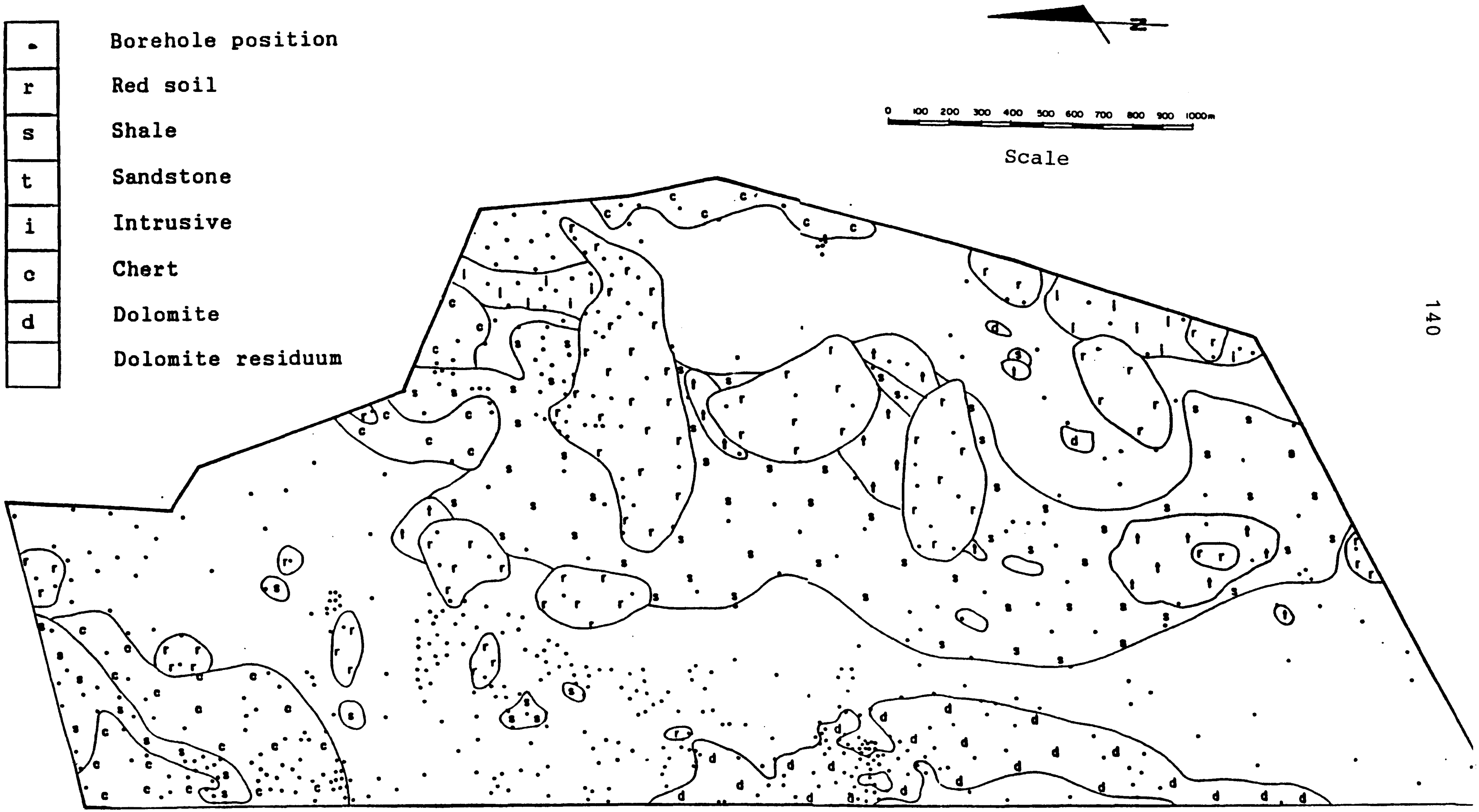


Figure 24: Geology of the study area and location of some of the boreholes (After Van Rooy 1984).

preliminary perspectives formulated concerning the geological and geohydrological characteristics of the site (e.g., depth to bedrock, bedrock types, soil types and water levels).

(ii) In excess of one hundred and thirty boreholes have been analysed in detail. These boreholes have been characterised according to the proposed method of scenario supposition.

The point characterisations have been transferred onto the gravity map and considered in conjunction with the other available engineering geological information including geology, remote sensing and soil data. A zones map has consequently been completed reflecting the stability characterisation of the site.

(iii) The occurrence of sinkholes and subsidences with respect to the various risk zones is then reviewed.

7.2.2 Additional Background Information.

This section provides additional pertinent background information, concerning the study area, which is judged to be of value in understanding the context in which the stability of site is being characterised.

a) Gravity survey:

A gravity survey of a portion of the study area was executed during May 1971 by the S.A. Geological Survey. The residual gravity contour information has been summarised by Van Rooy (1984) on a 1:5000 scale map (Figure 25). The survey was conducted on a 30m grid utilising a Worden gravimeter.

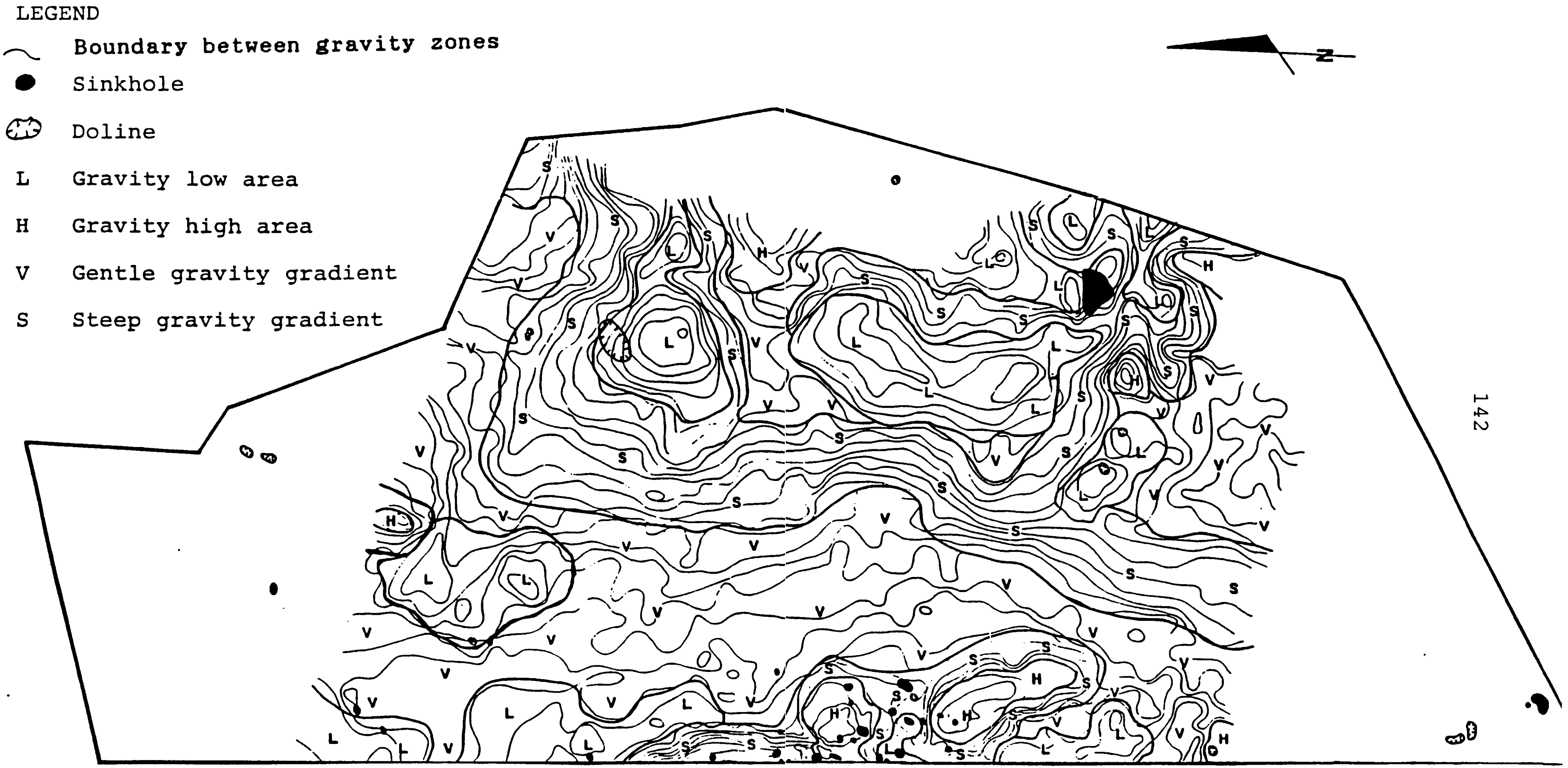


Figure 25: Gravity map of study area.

0 100 200 300 400 500 600 700 800 900 1000m

Scale

b) Infrared thermal linescan:

The thermal infrared linescan imagery gives a basic impression of heat emmitted from the surface of the earth. A composite survey of the study area is available as an invaluable tool. Use is made of tint, texture and patterns for interpretive purposes (Figure 26).

This imagery is most useful when used in conjunction with aerial photographic interpretation, providing additional information concerning the geology and soils. Structural features, such as fissures and faults, are readily detected in areas of shallow bedrock. Hartopp (1981) indicates that man's influence (e.g. agricultural development) surface water drainage, vegetation cover and thick cover soil all serve to diminish the thermal contrasts and the value of the technique.

c) Geohydrology:

No groundwater was encountered in any of the more than nine hundred and fifty boreholes drilled on the site. The water level is known to be at a depth in excess of 90m. Regional borehole data points to the water level being located at between 114m and 120m below ground level. Perched ground water conditions may exist on the Karoo shales and on the intrusives.

7.2.3 Stability Characterisation of the Site

The water level on the site is known to be well within dolomite bedrock. Consequently, any lowering of the water level will not have an influence on the stability of the site. The characterisation of the site is, therefore, affected within the context of a non -dewatering scenario. The mobilising agencies taken to be operative are therefore, ingress water, gravity and any "destabilising" ground vibrations. Receptacles of adequate, volume in relation to the potential development space, are assumed to be present in the bedrock and disseminated receptacles

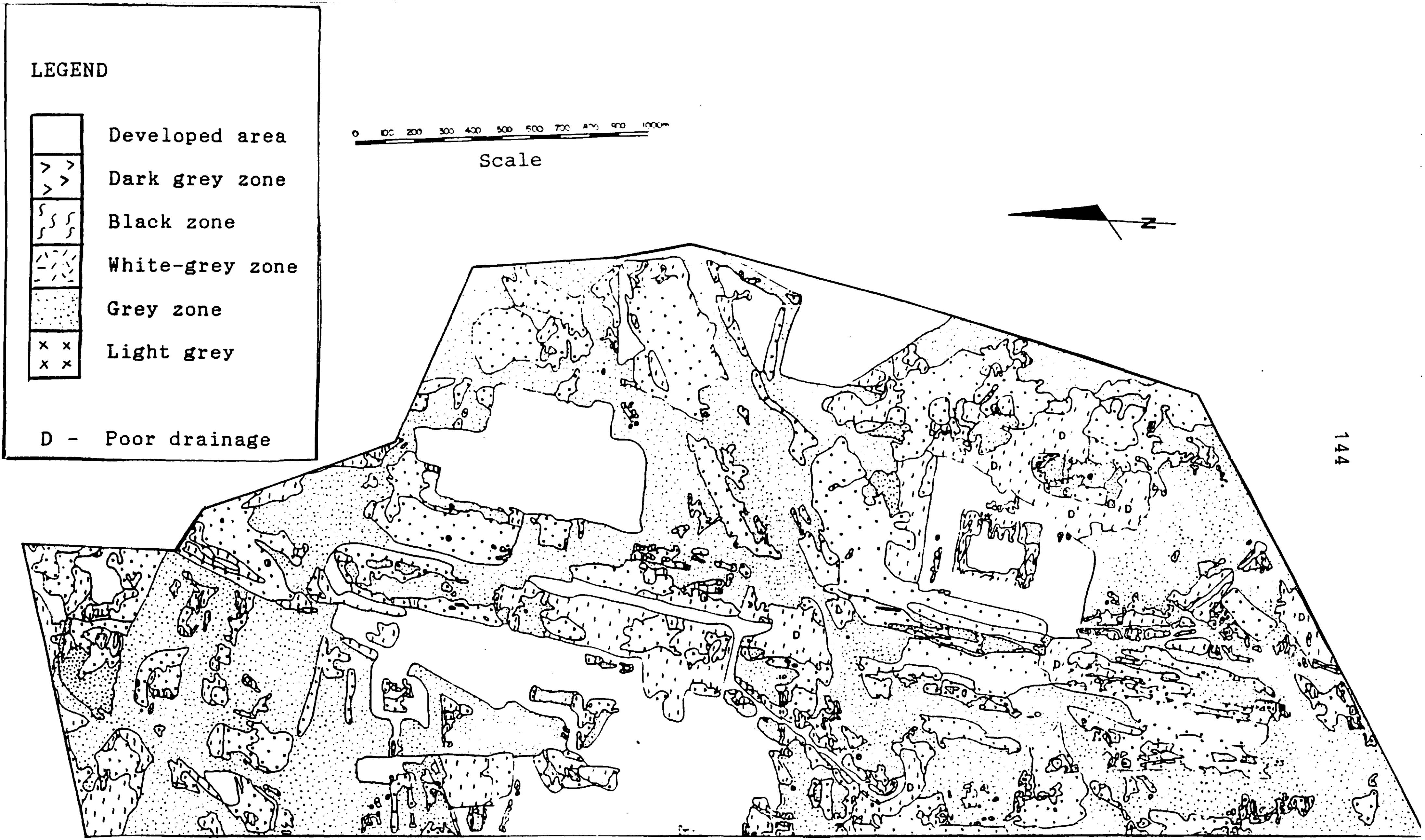


Figure 26: Thermal infrared imagery of the study area (After Van Rooy 1984).

are known to be present in certain types of superficial materials (e.g., chert rubble and fines).

The actual characterisation of the stability of the site is conducted within the frame-work proposed in Figure 20 entitled "Method of Scenario Supposition".

- **Step 1:** Desk Study of the Site: The 95 reports pertaining to the study area have been studied as has the other relevant available information. This information is summarised in the proceeding sections.

- **Step 2:** Preliminary zoning of the study area utilising tools such as remote sensing, gravity. Table 16 depicts the information utilised in formulating an initial perspective of the site.

- **Step 3:** Selection of boreholes to characterise the preliminary zoning of the site. One hundred and twenty seven of the most appropriately placed boreholes, have been analysed for the purposes of this study (Table 16).

- **Step 4:** Characterisation process (Scenario Supposition). Individual borehole profiles are reviewed in terms of the evaluation factors (Table 17) in the context of the selected non-dewatering scenario. Table 16 presents a summary of the assessment of the selected 127 boreholes.

The detailed characterisation procedure of a number of representative boreholes will be discussed below for demonstration purposes.

PART 1

ZONES	PEN RATE	BORE-HOLE NO.	COLLUVIUM/ AEROLIAN SANDS M	CHERT RESIDUUM		CHERT RUBBLE		KAROO SHALES / SANDSTONE M	INTRUSIVE SYNITE/ DIABASE	DOLOMITE RESIDUUM WAD/FERROAN SOIL	DOLOMITE BEDROCK	WATERTABLE	RISK CHARACTERISATION		POTENTIAL DEVELOPMENT SPACE DIAM.
				FINES PREDOM	FINES SUBORD M	FINES PREDOM M	FINES SUBORD M						DOLINE FORMATION	SINKHOLE FORMATION	
1		1	0-4		>15			4-15				IN BEDROCK	LOW RISK	LOW RISK	ALL
1		2						0-30				IN BEDROCK	LOW RISK	LOW RISK	ALL
1		3	0-9					9-30				IN BEDROCK	LOW RISK	LOW RISK	ALL
1		4	0-1,5					1,5-30				IN BEDROCK	LOW RISK	LOW RISK	ALL
1		5	0-12					12-30				IN BEDROCK	LOW RISK	LOW RISK	ALL
1		6	0-16					16-60				IN BEDROCK	LOW RISK	LOW RISK	ALL
1		7	0-7,5					7,5-30				IN BEDROCK	LOW RISK	LOW RISK	ALL
1		8	0-7,5					7,5-30				IN BEDROCK	LOW RISK	LOW RISK	ALL
1		9	0-31					31-90				IN BEDROCK	LOW RISK	LOW RISK	ALL
1		10	0-1,0		19,0-30			1-19				IN BEDROCK	LOW RISK	LOW RISK	LARGE
1		11	0-6,0		15-30			6,0-15				IN BEDROCK	LOW RISK	LOW RISK	LARGE
1		12						0-30				IN BEDROCK	LOW RISK	LOW RISK	ALL
1		13			6-30		0-4,5	4,5-6				IN BEDROCK	MEDIUM RSK	MEDIUM RISK	SMALL-LARGE
1		14	0-3,0					3,0-30				IN BEDROCK	LOW RISK	LOW RISK	ALL
1		15	0-13					13-30				IN BEDROCK	LOW RISK	LOW RISK	ALL
1		16	0-3					3-30				IN BEDROCK	LOW RISK	LOW RISK	ALL
1		17	0-7,0					7,0-30				IN BEDROCK	LOW RISK	LOW RISK	ALL
1		18	0-7,0					7,0-30				IN BEDROCK	LOW RISK	LOW RISK	ALL
1		19	0-21					21-30				IN BEDROCK	LOW RISK	LOW RISK	ALL
1		20	0-9					9-30				IN BEDROCK	LOW RISK	LOW RISK	ALL
1		21	0-9					9-30				IN BEDROCK	LOW RISK	LOW RISK	ALL
1		22	0-5		15-30			5-15				IN BEDROCK	LOW RISK	LOW RISK	LARGE

Table 16: Summary of borehole characteristics (non-dewatering scenario).

PART 2

ZONES	PEN RATE	BORE-HOLE NO.	COLLUVIUM/ AEROLIAN SANDS M	CHERT RESIDUUM		CHERT RUBBLE		KAROO SHALES / SANDSTONE M	INTRUSIVE SYNITE/ DIABASE	DOLOMITE RESIDUUM WAD/FERROAN SOIL	DOLOMITE BEDROCK M	CAVITY M	RISK CHARACTERISATION		POTENTIAL DEVELOPMENT SPACE DIAM.
				FINES PREDOM	FINES SUBORD M	FINES PREDOM M	FINES SUBORD M						DOLINE FORMATION	SINKHOLE FORMATION	
1		23	0-7,0		30-45			7-30				IN BEDROCK	LOW RISK	LOW RISK	ALL
1		24	0-12					0-30				IN BEDROCK	LOW RISK	LOW RISK	ALL
1		25	0-2					2-30				IN BEDROCK	LOW RISK	LOW RISK	ALL
1		26	0-3					3-60				IN BEDROCK	LOW RISK	LOW RISK	ALL
1		27	0-9		46-60			9-46				IN BEDROCK	LOW RISK	LOW RISK	ALL
1		28	0-4		7,0-60			4-7				IN BEDROCK	LOW RISK	LOW RISK	ALL
1		29			4,0-30		0-4	12-30				IN BEDROCK	HIGH RISK	HIGH RISK	SMALL
1		30			0-30							IN BEDROCK	HIGH RISK	HIGH RISK	SMALL
1		31	0-12				0-3	3-30				IN BEDROCK	LOW RISK	LOW RISK	?
3		32			0-30								HIGH-LOW	HIGH	SMALL
3		33								TRACE 7-15	0-30		HIGH	HIGH	SMALL
2		34			6-30		0-6						MEDIUM	MEDIUM	SMALL-MEDIUM
2		35			6-30	0-6							MEDIUM	MEDIUM	SMALL-MEDIUM
3		36			3-30		0-3						HIGH	HIGH	SMALL
2		37			9-30	0-3	3-9						MEDIUM	MEDIUM	SMALL-MEDIUM
1		38	0-31						31-41				LOW	LOW	-
2		39				0-15			15-30		30-36		MEDIUM	MEDIUM	SMALL-MEDIUM
3		40			4-30		0-4						HIGH	HIGH	SMALL-MEDIUM
3		41			0-30								HIGH	HIGH	SMALL
2		42		4-7	7-22		0-4			22-49;54-60		49-54	MEDIUM	MEDIUM	SMALL-MEDIUM
2		43		16-60	5-16		0-5						MEDIUM	MEDIUM	MEDIUM
2		44		15-19	0-15; 19-30								MEDIUM	MEDIUM	MEDIUM-LARGE
2		45		10-30		0-6							MEDIUM	MEDIUM	MEDIUM

Table 16: Summary of borehole characteristics (non-dewatering scenario)- continued.

PART 3

ZONES	PEN RATE	BORE-HOLE NO.	COLLUVIUM/ AEOLINE SANDS	CHERT RESIDUUM		CHERT RUBBLE		KAROO SHALES / SANDSTONE M	INTRUSIVE SYNITE/ DIABASE M	DOLOMITE RESIDUUM WAD/FERROAN SOIL M	DOLOMITE BEDROCK M	CAVITY M	RISK CHARACTERISATION		POTENTIAL DEVELOPMENT SPACE DIAM.
				FINES PREDOM	FINES SUBORD M	FINES PREDOM M	FINES SUBORD M						DOLINE FORMATION	SINKHOLE FORMATION	
2		46				0-10				10-30			MEDIUM	MEDIUM	MEDIUM-LARGE
2		47			3-11		0-3			10-33	33-50		MEDIUM	MEDIUM	MEDIUM-LARGE
3		48			3-30		0-3						HIGH	HIGH	SMALL
2		49			11-60		0-11						MEDIUM	MEDIUM	MEDIUM
1		50			6-60		0-3	3-6					LOW	LOW	MEDIUM
		31													
2		52					0-30						MEDIUM	MEDIUM	SMALL-LARGE
2		53	8-60			0-8							MEDIUM	MEDIUM	SMALL-LARGE
3		54			1-30		6-1						HIGH	HIGH	SMALL
2		55			13-30	0-13							MEDIUM	MEDIUM	SMALL-MEDIUM
1		56	0-60										LOW	LOW	-
2		57					0-18		18-30				MEDIUM	MEDIUM	SMALL-MEDIUM
2		58		9-30			0-9						MEDIUM	MEDIUM	MEDIUM-LARGE
2		59				0-60							MEDIUM	MEDIUM	SMALL-LARGE
2		60			15-30		0-15						MEDIUM	MEDIUM	SMALL-LARGE
1		61			19-30				0-19				LOW	LOW	
1		62	0-2						2-30				LOW	LOW	-
2		63	12-25				0-12	25-30					MEDIUM	MEDIUM	MEDIUM
1		64					0-3	3-30					LOW	LOW	-
2	2-5	65			5-30		0-5						MEDIUM	MEDIUM	MEDIUM
2	0-5	66			5-30		0-5						MEDIUM	MEDIUM	MEDIUM
2		67		25-30	6-25		0-6						MEDIUM	MEDIUM	MEDIUM
2		68			5-30	3-5	0-3						MEDIUM	MEDIUM	MEDIUM

Table 16: Summary of borehole characteristics (non-dewatering scenario)- continued.

PART 4

ZONES	PEN RATE	BORE-HOLE NO.	COLLUVIUM/ AEOLINE SANDS M	CHERT RESIDUUM		CHERT RUBBLE		KAROO SHALES / SANDSTONE M	INTRUSIVE SYNITE/ DIABASE M	DOLOMITE RESIDUUM WAD/FERROAN SOIL M	DOLOMITE BEDROCK M	CAVITY M	RISK CHARACTERISATION		POTENTIAL DEVELOPMENT SPACE DIAM.
				FINES PREDOM M	FINES SUBORD M	FINES PREDOM M	FINES SUBORD M						DOLINE FORMATION	SINKHOLE FORMATION	
2	4-6	69			5-30		0-5						MEDIUM	MEDIUM	MEDIUM
2		70			3-30		0-3						MEDIUM	MEDIUM	MEDIUM
2		71			3-30		0-3						MEDIUM	MEDIUM	MEDIUM
2		72			0-30								MEDIUM	MEDIUM	SMALL
2		73					0-10			10-30			MEDIUM	MEDIUM	SMALL-LARGE
2		74			5-30		0-5						MEDIUM	MEDIUM	SMALL-MEDIUM
2		75			2-30		0-2						MEDIUM	MEDIUM	SMALL
2	6-8 35-45	76			6-60		0-6						MEDIUM	MEDIUM	MEDIUM
2	8-10 20-23	77			5-30	0-5							MEDIUM	MEDIUM	SMALL-MEDIUM
2		78			2-30		0-2						MEDIUM	MEDIUM	SMALL
2	0-3 8-20	79	0-3		3-30								MEDIUM	MEDIUM	SMALL-MEDIUM
2		80			3-30		0-3						MEDIUM	MEDIUM	SMALL
3	0-4	81					0-5				5-25		HIGH	HIGH	SMALL-MEDIUM
3	0-6	82					0-6				6-24		HIGH	HIGH	SMALL-MEDIUM
2		83			2-30		0-2						MEDIUM	MEDIUM	MEDIUM
2	0-6	84					0-3			3-6	6-24		MEDIUM	MEDIUM	MEDIUM
2	20-23 8-10	85			5-30		0-5						MEDIUM	MEDIUM	MEDIUM
3		86					0-1				1-10		HIGH	HIGH	SMALL
3		87			1-30		0-1				1-10		HIGH	HIGH	SMALL
2	0-6	88					0-6				6-10		MEDIUM	MEDIUM	MEDIUM
2	1-10	89					0-10				10-13		MEDIUM	MEDIUM	MEDIUM
3	0-23	90		8-10			0-8				23-27	10-23	HIGH	HIGH	LARGE

Table 16: Summary of borehole characteristics (non-dewatering scenario)- continued.

PART 5

ZONES	PEN RATE	BORE-HOLE NO.	COLLUVIUM/ AEOLINE SANDS M	CHERT RESIDUUM		CHERT RUBBLE		KAROO SHALES / SANDSTONE M	INTRUSIVE SYNITE/ DIABASE M	DOLOMITE RESIDUUM WAD/FERROAN SOIL M	DOLOMITE BEDROCK M	CAVITY M	RISK CHARACTERISATION		POTENTIAL DEVELOPMENT SPACE DIAM.
				FINES PREDOM M	FINES SUBORD M	FINES PREDOM M	FINES SUBORD M						DOLINE FORMATION	SINKHOLE FORMATION	
3	0-31	91		4-6			0-4				>31	6-31		HIGH	LARGE
		92	)												
		93	) OLD BOREHOLE LOGS - UNRELIABLE												
		94	)												
		95	)												
		96	)												
3	0-30	97				0-40						30-40	HIGH RISK	HIGH	HIGH
2	7-14	98					0-4				4-10		MED. RISK	MEDIUM	MEDIUM
3		99			7-11		0-1				1-7	11-14	HIGH	HIGH	SMALL
3	0-4	100					0-1				4-10	1-4	HIGH	HIGH	SMALL-MEDIUM
3		101					0-1				1-10		HIGH	HIGH	SMALL
3		102					0-1				1-10		HIGH	HIGH	SMALL
3	2-3	103					0-3				3-10		HIGH	HIGH	SMALL-MEDIUM
3	0-2	104					0-2				2-10		HIGH	HIGH	SMALL
3	0-3	105					0-3				3-10		HIGH	HIGH	SMALL-MEDIUM
3		106					0-1				1-10		HIGH	HIGH	SMALL
3		107					0-1				1-10		HIGH	HIGH	SMALL
3	0-29	108					0-13			13-28,24-30		18-24	HIGH	HIGH	MEDIUM-LARGE
3	0-13	109					0-14				14-20		HIGH	HIGH	MEDIUM-LARGE
3	0-11	110					0-11				11-20		HIGH	HIGH	MEDIUM-LARGE
3	19-25	111		9-22			0-9			33-54			MED.-HIGH	MED.-HIGH	MEDIUM-LARGE
3	34-46	112		14-46			0-14						HIGH	HIGH	MEDIUM-LARGE
3	33-54	113			11-54		0-11						HIGH	HIGH	MEDIUM-LARGE
3	8-30	114			3-36		0-3						HIGH	HIGH	MEDIUM-LARGE

Table 16: Summary of borehole characteristics (non-dewatering scenario)- continued.

PART 6

ZONES	PEN RATE	BORE-HOLE NO.	COLLUVIUM/ AEDLINE SANDS M	CHERT RESIDUUM		CHERT RUBBLE		KAROO SHALES / SANDSTONE M	INTRUSIVE SYNITE/ DIABASE M	DOLOMITE RESIDUUM WAD/FERROAN SOIL M	DOLOMITE BEDROCK M	CAVITY M	RISK CHARACTERISATION		POTENTIAL DEVELOPMENT SPACE DIAM.
				FINES PREDOM M	FINES SUBORD M	FINES PREDOM M	FINES SUBORD M						DOLINE FORMATION	SINKHOLE FORMATION	
3	29-44	115			8-44		0-8						HIGH	HIGH	MEDIUM-LARGE
3 3	43-54 29-44	116 115		7-54	8-44		0-7 0-8						HIGH HIGH	HIGH HIGH	MEDIUM-LARGE MEDIUM-LARGE
3	43-54	116		7-54			0-7						HIGH	HIGH	MEDIUM-LARGE
2		117		16-30	5-16		0-5						MEDIUM	MEDIUM	MEDIUM
2		118			6-30		0-6						MEDIUM	MEDIUM	MEDIUM-LARGE
2	18-26	119			5-30		0-5						MEDIUM	MEDIUM	MEDIUM-LARGE
2		120			13-30		0-13						MEDIUM	MEDIUM	MEDIUM-LARGE
2		121			6-30		0-6						MEDIUM	MEDIUM	MEDIUM-LARGE
2		122			5-30		0-5						MEDIUM	MEDIUM	LARGE
3		123			3-30		0-3						HIGH	HIGH	SMALL
3		124			0-30								HIGH	HIGH	SMALL
2		125		10-30			0-10						MEDIUM	MEDIUM	LARGE
3		126		3-30			0-3						HIGH	HIGH	SMALL-MEDIUM
3		127		2-30			0-2						HIGH	HIGH	SMALL
3		128					0-31						HIGH	HIGH	SMALL

Table 16: Summary of borehole characteristics (non-dewatering scenario)- continued.

Each borehole is reviewed with respect to the following evaluation factors shown in Table 17.

Table 17: Evaluation factors for sinkhole and doline formation

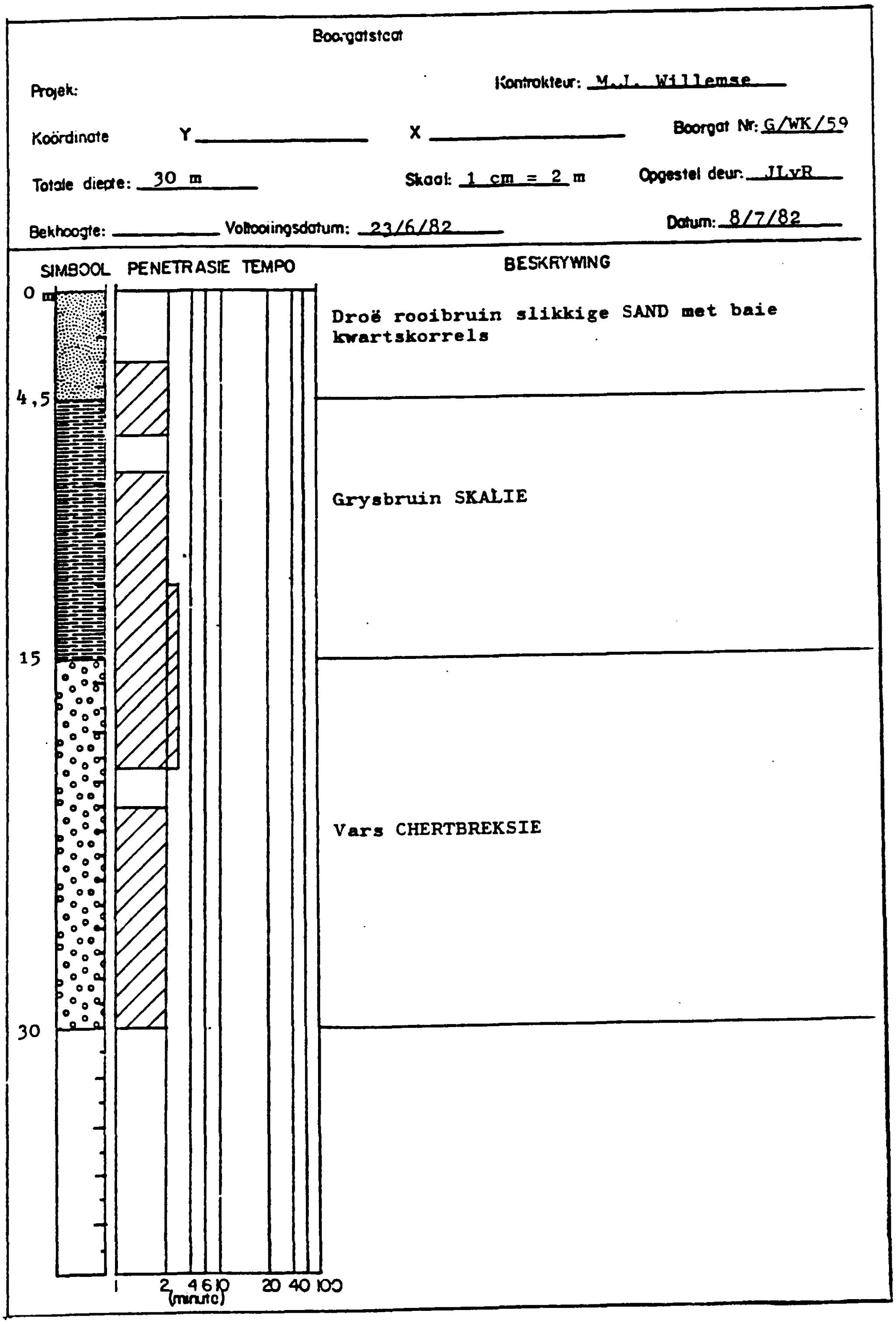
EVALUATION FACTORS	
SINKHOLE FORMATION	**DOLINE FORMATION**
Mobilising Agency/ Agencies **Receptacle Development** **Potential Development Space** **Nature Blanketing Layers** **Mobilisation Potential**	**Mobilising Agency** **Nature Blanketing Layer/s** **Mobilisation Potential** **Lateral Extent**

Randomly selected sample boreholes are evaluated below:

(i) Borehole 1: (Figure 27 and Table 16).

This borehole is located on an area of gentle gravity gradient. No perched groundwater was encountered. The groundwater level is located below a depth of 114m within dolomite bedrock. The borehole reveals that the subsurface profile consists of 4.5m of aeolian sands overlying 11.5m of Karoo shales. At a depth of 15m to 30m chert breccia was noted. No sample or air losses were noted. No cavities were intercepted (Figure 27).

Potential receptacles are expected to occur below a depth of 15m in the chert. The "blanketing layer" overlying these receptacles consists of Karoo shales and the aeolian sands. The shales act as a aquitard or aquiclude, retarding or precluding water ingress. Sub-surface erosion cannot be initiated, consequently the "blanketing layer" is judged to have a low mobilisation potential. In addition the angle of the draw in the shales and sandstones is taken as 90 degrees resulting in a very small potential development space being projected essentially within the aeolian sands with an angle of draw of 60 degrees. The former is based on experience and observation, the latter on the research of Bennet (1980) and Wilkinson (1983).



Boorgatstaat

Projek:
Kontrakteur: M.J. Willemse
Koördinate Y ____ X ____
Boorgat Nr: G/WK/59
Totale diepte: 30 m
Skaal: 1 cm = 2 m
Opgestel deur: JLvR
Bekhoogte: ____
Voltooiingsdatum: 23/6/82
Datum: 8/7/82

SIMBOOL PENETRASIE TEMPO BESKRYWING

0 m – 4,5: Droë rooibruin slikkige SAND met baie kwartskorrels

4,5 – 15: Grysbruin SKALIE

15 – 30: Vars CHERTBREKSIE

Figure 27: Borehole 1; Profile

The mobilisation potential of the materials with respect to doline formation is also judged to be low as ingress water cannot affect any damage to the profile.

The subsurface conditions represented in borehole 1 are characterised as reflecting a low risk of doline and sinkhole formation in the context of a non-dewatering scenario.

(ii) Borehole 39: (Figure 28 and Table 16)

Borehole 62 is located in a gravity low. No perched or dolomitic ground water was encountered.

The borehole reveals that the subsurface profile consists of 15m of chert rubble and fines. This material overlies a syenite intrusive which is noted to occur between 15m and 30m depth. Dolomite bedrock is intercepted from 30m to 36m. Conservative assessment necessitates that receptacles are assumed to be present in the dolomite bedrock. Disseminated receptacles are known to typically occur in the chert rubble and fines. The potential development space related to the disseminated receptacles is estimated to be of a medium" size. The potential development space as associated with the receptacles in the bedrock is estimated as "Large" (Figure 28).

The blanketing layer covering the deeper receptacles within the bedrock essentially consists of chert rubble and fines, and intrusive. The rubble and fines contain a multitude of potential flow paths and are susceptible to erosion under the sustained influence of a mobilising agency such as water. This component of the blanketing layer reflects a medium susceptibility to mobilisation. The lower component of the blanketing layer consists of intrusive. The intrusive horizon acts as an aquiclude or aquitard, retarding or precluding water ingress. Erosion or piping erosion cannot be initiated. This significant horizon displays a low mobilisation potential.

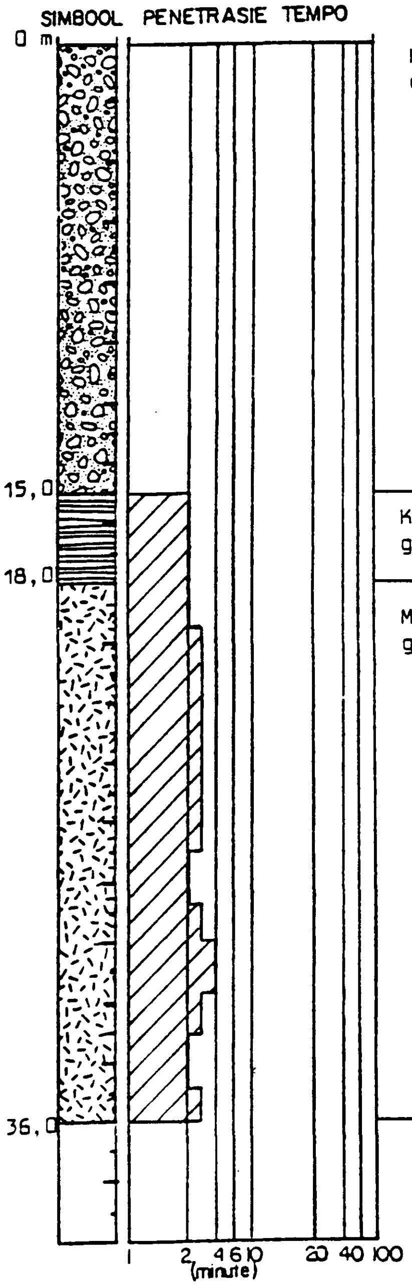
Boorgatstaat

Projek: ____________ Kontrakteur: ____________

Koördinate Y ____________ X ____________ Boorgat Nr: ______

Totale diepte: 36m Skaal: 1 cm = 2 m Opgestel deur: JLvR

Bekhoogte: ________ Voltooiingsdatum: 1/11/82 Datum: 11/1182



BESKRYWING

Klam rooibruin kleiige SLIK met min geloogde chertgruis.

Klam groenbruin sandige KLEI (verweerde stollingsgesteente)

Matig verweerde stollingsgesteente met klam groenbruin sandige klei.

Figure 28: Borehole 39; Profile.

Consequently the material with the "large development space" is protected from mobilisation by the operative agencies. The blanketing layer associated with the disseminated receptacles reflects a different potential susceptibility to the activities of a mobilising agency such as ingress water. The blanketing layer consists of chert rubble and fines. As indicated above, these materials reflect a "medium susceptibility to mobilisation". The material within the medium size development space reflects a "medium risk" of succumbing to the activities of the mobilising agency.

Doline formation is also feasible within the chert rubble horizon. In a profile such as this, where the fines predominate, the downward transportation of fines will cease if the mobilising agency is not sustained or if the receptacles are choked. This borehole profile is, consequently, characterised as displaying a medium risk of doline and small to medium size sinkhole formation.

(iii) Borehole 62: (Figure 29 and Table 16)

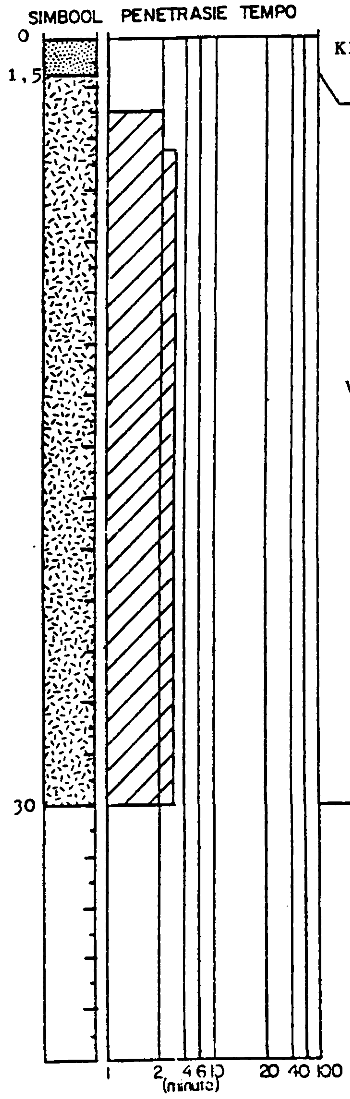
Borehole 62 is located on a gravity low. No perched water table is noted. The dolomitic watertable was not intersected.

The borehole indicates that subsurface profile consists of 2m of aeolian sand overlying 28m of intrusive. Receptacles are most likely located at great depth. The blanketing layer is constituted by either an aquiclude or aquitard. The material of this layer, therefore, has a low mobilisation potential.

The borehole profile is characterised as reflecting a low risk of either sinkhole or doline formation. The only settlement that may occur will be related to the collapse potential of the aeolian sands which are known to possess a collapsible fabric.

Boorgatstaat

Projek: Waterkloof LMB
Kontrakteur: M.J. Willemse
Koördinate Y ______ X ______
Boorgat Nr: G/WK/1
Totale diepte: 30 m
Skaal: 1 cm = 2 m
Opgestel deur: JLvR
Bekhoogte: ______
Voltooiingsdatum: 4/12/81
Datum: 4/1/82



BESKRYWING

Klam rooibruin sandige SLIK

Verweerde STOLLINGSGESTEENTE (DIABAAS)

Figure 29: Borehole 62; Profile.

(iv) Borehole 102: (Figure 30 and Table 16)

Borehole 102 is located on a gravity high. The groundwater level is within the bedrock. The profile consists of 1m of chert rubble and fines overlying dolomite bedrock at 1m. (Figure 30). The potential receptacles are assumed to be at a very shallow depth in scattered outcrop and outcrop areas. The bedrock/soil interface is at shallow depth. Ingress water readily exploits this interface. It therefore takes very little water to induce subsurface erosion.

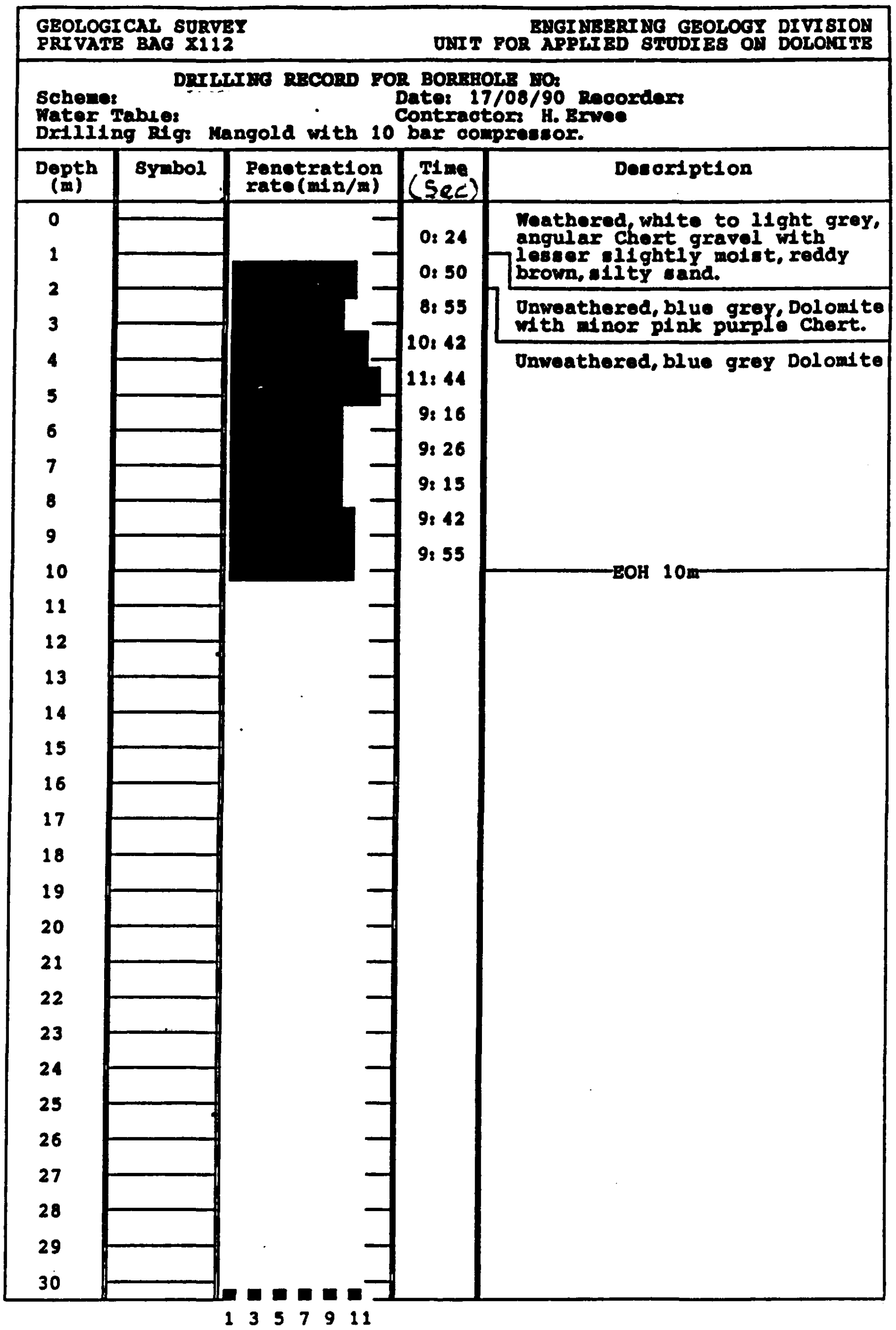
Furthermore, the installation of services in areas of shallow bedrock may involve blasting, seriously disturbing the metastable environment. The thin blanketing layer is characterised as reflecting a great susceptibility to mobilisation. The potential development space is confined to "small" due to shallow receptacle development and the confining affect of the rock.

This borehole profile is characterised as reflecting a high risk of small sinkhole and doline formation.

(v) Borehole 100: (Figure 31 and Table 16)

Borehole 100 is located on a gravity gradient. The water table is located at great depth and was not intersected in this borehole.

The borehole intersected dolomite bedrock at 4m. The upper 4m of profile consists of 1m of chert rubble and fines overlying a 3m cavity. Sample loss and penetration rates of 3 or 4 seconds confirm the presence of the cavity. Receptacles are assumed to be present in the bedrock whereas disseminated receptacles are known to occur in the chert rubble. The base of the chert rubble layer is co-incident with the bedrock interface. The disseminated receptacles and receptacles are assumed to be at the same depth. The potential development space is estimated as of "medium" size.



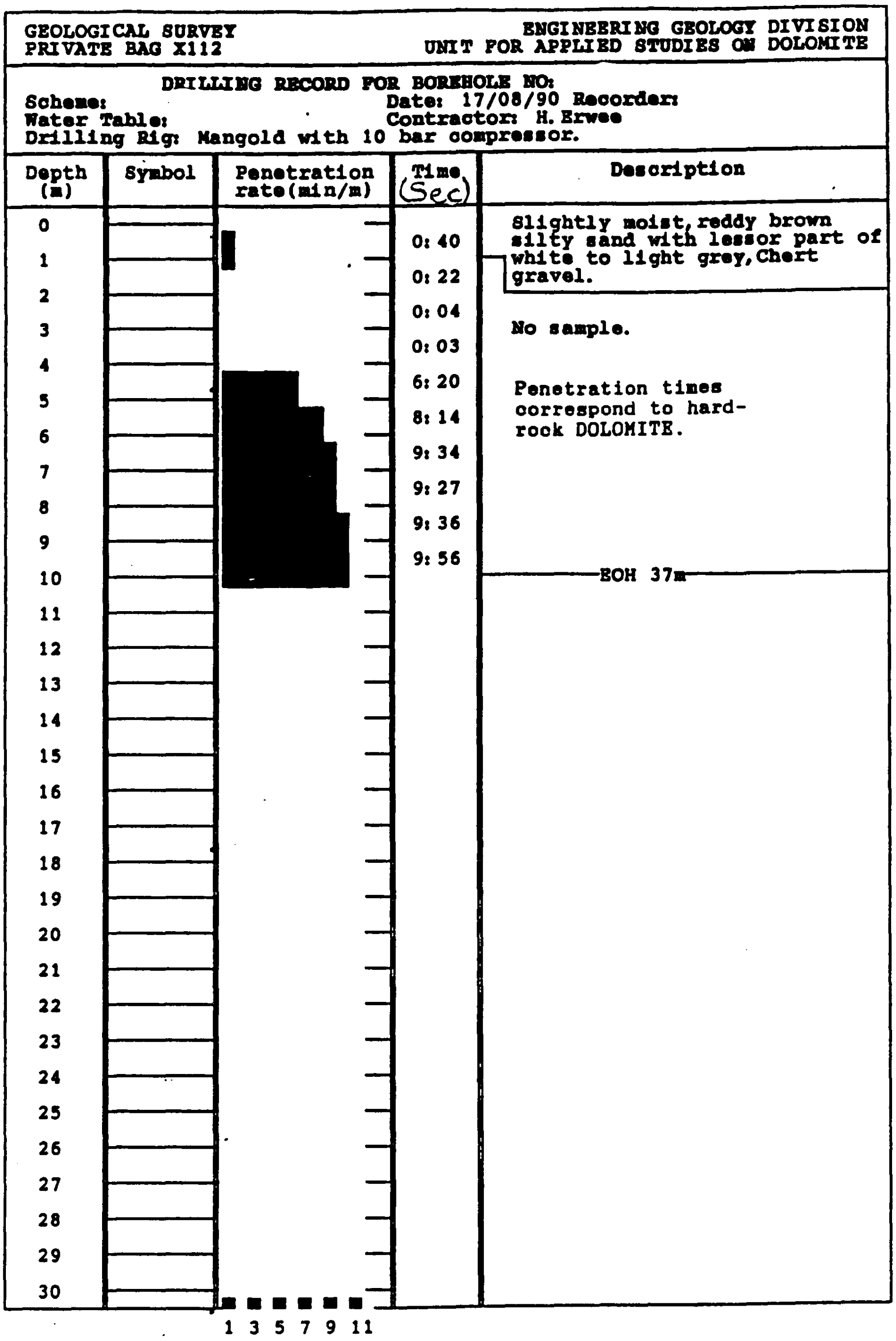
GEOLOGICAL SURVEY
PRIVATE BAG X112

ENGINEERING GEOLOGY DIVISION
UNIT FOR APPLIED STUDIES ON DOLOMITE

DRILLING RECORD FOR BOREHOLE NO:
Scheme: **Date:** 17/08/90 **Recorder:**
Water Table: **Contractor:** H. Erwee
Drilling Rig: Mangold with 10 bar compressor.

Depth (m)	Symbol	Penetration rate(min/m)	Time (Sec)	Description
0			0: 24	Weathered, white to light grey, angular Chert gravel with lesser slightly moist, reddy brown, silty sand.
1			0: 50	
2			8: 55	Unweathered, blue grey, Dolomite with minor pink purple Chert.
3			10: 42	
4			11: 44	Unweathered, blue grey Dolomite
5			9: 16	
6			9: 26	
7			9: 15	
8			9: 42	
9			9: 55	
10				EOH 10m
11				
12				
13				
14				
15				
16				
17				
18				
19				
20				
21				
22				
23				
24				
25				
26				
27				
28				
29				
30				

Figure 30: Borehole 102; Profile.



GEOLOGICAL SURVEY
PRIVATE BAG X112

ENGINEERING GEOLOGY DIVISION
UNIT FOR APPLIED STUDIES ON DOLOMITE

DRILLING RECORD FOR BOREHOLE NO:
Scheme: **Date:** 17/08/90 **Recorder:**
Water Table: **Contractor:** H. Erwee
Drilling Rig: Mangold with 10 bar compressor.

Depth (m)	Symbol	Penetration rate (min/m)	Time (Sec)	Description
0			0: 40	Slightly moist, reddy brown silty sand with lessor part of white to light grey, Chert gravel.
1			0: 22	
2			0: 04	
3			0: 03	No sample.
4			6: 20	
5			8: 14	Penetration times correspond to hard-rock DOLOMITE.
6			9: 34	
7			9: 27	
8			9: 36	
9			9: 56	
10				EOH 37m
11				
12				
13				
14				
15				
16				
17				
18				
19				
20				
21				
22				
23				
24				
25				
26				
27				
28				
29				
30				

Figure 31: Borehole 100: Profile.

A blanketing layer of chert rubble and fines is known to be susceptible to subsurface erosion. This material would normally be characterised as reflecting a medium risk of mobilisation. Abuse of the area around this borehole is evident in the poor surface water management practised. The cavity intersected at shallow depth indicates that the process of sinkhole formation is underway. The subsurface conditions in this borehole must be characterised as reflecting a high risk of doline and small to medium size sinkhole formation.

- **Step 5:** Pooling of individual borehole characterisation and amending of preliminary zoning. (Figure 32).

  The characterisation boreholes are evaluated within the context of the geological and geomorphological setting in which they are placed. The remote sensing and gravity information is consulted for further guidance on the lateral extent of the conditions encountered in the representative boreholes. The characterisations of the individual boreholes within a potential zone are pooled e.g., boreholes displaying a high risk of small to medium size sinkholes and dolines forming. If several boreholes confirm a particular characterisation, that zone will be defined accordingly. In those areas where marked deviations occur, the zoning is modified by the creation of separate zones.

- **Step 6:** The evaluation process culminates in the finalised zoning of the stability of the site. The study area has been sub-divided into the following five zones:

- **Zone 1:** Low risk of either any size sinkhole or doline forming.

- **Zone 2.1:** Medium risk of doline and small to medium size sinkhole formation.

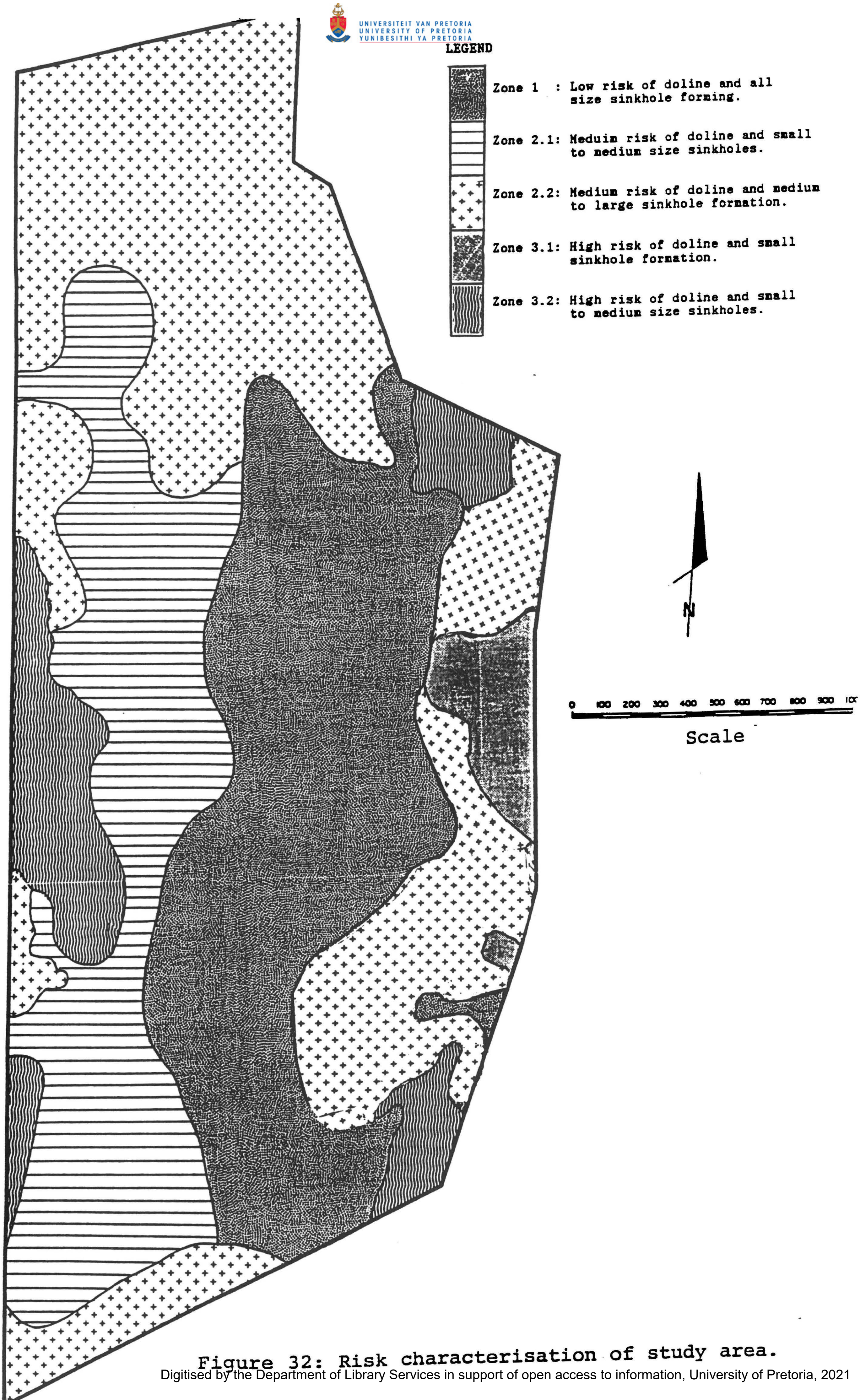


Figure 32: Risk characterisation of study area.

- **Zone 2.2:** Medium risk of doline and medium to large size sinkhole formation.

- **Zone 3.1:** High risk of doline and small sinkhole formation.

- **Zone 3.2:** High risk of doline and small to medium size sinkhole formation.

Conservatively characterised boreholes are included with the most predominant conservative assessment for a particular zone. For example a zone predominantly characterised as reflecting a high risk of doline and small to medium size sinkhole formation may include limited pockets of ground characterised as low risk.

Stability characterisations and forty six ground movement events, including sinkholes and dolines have been recorded within the delineated study area.

The distribution of these sinkholes and dolines with respect to the characterised zones is a follows:

Zone 1: **Low risk:** No sinkholes or dolines recorded in this delineated area.

Zone 2: **Medium Risk:** Nine recorded sinkholes and seven dolines have occurred in this delineated area.

Zone 3: **High Risk:** Thirty sinkholes and three dolines have occurred in this zone.

The ground movement events in the medium risk area are recorded as follows:

Zone 2.1: **Medium Risk of Doline and Small to Medium Size Sinkholes:** Two small, three medium and one large sinkhole and two dolines. i.e., 1 in 8 events exceed expectation or alternatively 12% of events can be expected to exceed predictions.

Zone 2.2: Medium Risk of Doline & Large Sinkholes Forming: Two large sinkholes, one medium, sinkhole, and 5 dolines.

Table 18: Ground movement events (sinkholes and dolines) in the identified various stability zones.

STABILITY ZONE	RISK CHARACTERISATION	NO. GROUND MOVEMENT EVENTS	EVENTS PER Ha
1	LOW	0	0/ha
2	MEDIUM	16	0.07/ha
3	HIGH	33	0.7/ha

The ground movement in the high risk area are as follows:

Zone 3: High Risk of Doline & Small to Medium Size Sinkholes: Nine small, seventeen medium and 4 large sinkholes and three dolines. i.e., 1 in 8 events exceed the predicted size or 12% of the events can be expected to exceed the predicted size.

There is more land in Zone 2 (+-90ha) covered by intensive development than in Zone 3 (40 ha). Six ground movement events have been recorded in the 90ha of medium risk ground while 20 events have been noted in the 40ha constituting the high risk area. In other words **there are 0,07 events/ha in the medium risk area of intensive development as opposed to 0,7 events/ha in the high risk area of intensive development.** Consequently there are 10 times more events in the high risk than in the medium risk zone.

The low risk area embraces approximately 520 ha of land. No events have been recorded in this area. Structures in this zone have been damaged due to differential settlements resulting from the inundation of soils with a collapsible fabric.

It is important to note that the determination of the angle of draw utilised is dependent on the engineering geologist's experience. The more accurately the assessment of conditions and selection of the angles, the more successful will be the predictions of the system. Obviously these values are dependent on the nature and geotechnical characteristics of the various soil and rock materials being assessed, particularly the angle of repose which includes the joint influences of the angle of internal friction and cohesion.

It must be emphasised, that the prediction of the size of features is only meant as a rule of thumb. **The characterisation of the risk categories is the most important element of the evaluation process.**

The intention is to ensure discussion of the factors that are crucial to the evaluation of the stability of a site. The characterisation of the stability of a site is completed in order to provide a guide to the selection of appropriate remedial and precautionary measures.

7.3 Review of the dewatering scenario.

7.3.1 General.

The review of the dewatering scenario will not be discussed in the same detail as the non-dewatering scenario. This study is merely aimed at elaborating on the findings of the assessment of the former scenario. The records of a number of ground movement events in areas subjected to dewatering, have been selected randomly for the purposes of this study. The ground movement event, the karstification and the boreholes that characterise the subsurface conditions on a particular gravity feature, are reviewed in the context of "case study areas". Information reviewed with respect to each case study area includes location, geological setting (e.g. formation), geophysical data, geohydrological data, borehole and other engineering geological information. Based on this information, the stability of a limited area around a ground movement site (i.e. within a "case study area"), is characterised and the results reviewed. Twenty such case study areas have been randomly selected and studied.

7.3.2 Stability characterisation of the selected study case areas.

The subsurface conditions, stability characterisations, predictions and scale of actual ground movement events are presented in Table 19. As in the case of the study presented in section 7.2, the available information has been studied and preliminary perspectives formulated concerning the geological and geohydrological characteristics of the various sites e.g. depth to bedrock, bedrock types, water levels etc. The occurrence of sinkholes and subsidences with respect to the various risk characterisations is then reviewed. Obviously the prime mobilising agency in this scenario is the process of watertable drawdown. A number of potential agencies must, however, be considered to be operative in the profile including waterlevel drawdown, ingress water, gravity and ground vibrations.

Table 19: Summary of borehole characteristics (dewatering scenario).

PART 1

CASE STUDY AREA	BORE HOLE NO.	GRAVITY FEATURE	COLLUVIUM AEOLIAN SANDS ALLUVIUM (M)	CHERT RUBBLE (M)	CHERT RESIDUUM		PRETORIA(P) KAROO(K) ROCKS (M)	INTRUSIVE	DOLOMITE RESIDUUM INCLUDING WAD/FERROAN SOIL	DOLOMITE BEDROCK (M)	POOR DRILLING CONDITIONS/ NSR/RP ETC. (M)	CAVITY (M)	ORIGINAL WATER (M)	RISK CHARACTERISATION				POTENTIAL SINKHOLE DEVELOPMENT SPACE		FINAL CHARACTERISATION AMALGAMATED SCENARIO			ACTUAL RECORDED EVENT	
														DOLINE FIRMATION		SINKHOLE FORMATION								
					FINES PREDOM (M)	FINES SUBORD (M)								W.L.	INGRESS WATER	W.L.	INGRESS WATER	WOLODRWDN	INGRESS WATER	DOLINE	SINKHOLE	DEVELOPMENT SPACE	SINKHOLE/DOLINE	CAUSE
1	1	GRADIENT	0-4			4-76			76-1037	103	80-103		100	LOW	MEDIUM	LOW	MEDIUM	V.LARGE	V.LARGE	MEDIUM	MEDIUM	V.LARGE	V.LARGE DOLINE	INGRESS WATER
	2	GRADIENT	0-4	4-13					13-93M	93	13-93		100	LOW	MEDIUM	LOW	MEDIUM	ALL	V.LARGE	MEDIUM	MEDIUM	V.LARGE	V.LARGE DOLINE	INGRESS WATER
	3	GRADIENT	0-3			11-38	3-11 (K)		38-60M				100	HIGH	LOW	HIGH	LOW	V.LARGE	ALL	HIGH	HIGH	V.LARGE	V.LARGE DOLINE	INGRESS WATER
	4	GRADIENT	0-3			3-61			61-101	101			100	LOW	MEDIUM	LOW	MEDIUM	ALL	V.LARGE	MEDIUM	MEDIUM	V.LARGE	V.LARGE DOLINE	INGRESS WATER
	5	GRADIENT	0 -7		29-37	7-29			37-100		37-100		100	HIGH	HIGH	HIGH	HIGH	V.LARGE	V.LARGE	HIGH	HIGH	V.LARGE	V.LARGE DOLINE	INGRESS WATER
2	6	GRADIENT	0-4				4-10 (K)		10-68		59-68		24	HIGH	LOW	HIGH	LOW	V.LARGE	ALL	HIGH	HIGH	V.LARGE	V.LARGE DOLINE	WATERLEVEL DRWDN
	7	GRADIENT	0-82										25	HIGH	LOW	HIGH	LOW	V.LARGE	ALL	HIGH	HIGH	V.LARGE	V.LARGE DOLINE	WATERLEVEL DRWDN
	8	GRADIENT	0-4,15-22	4-15					22-40 & 47-52	52	40-47	40-47	24	HIGH	MEDIUM	HIGH	MEDIUM	V.LARGE	V.LARGE	HIGH	HIGH	V.LARGE	V.LARGE DOLINE	WATERLEVEL DRWDN
3	9	HIGH	0-6						9-22	22	9-22		140	LOW	HIGH	LOW	HIGH	V.LARGE	LARGE	HIGH	HIGH	V.LARGE	1 MEDIUM, 3 LARGE AND 1 V.LARGE SINKHOLE	INGRESS WATER
	10	HIGH	0-5		5-9					9			140	LOW	MEDIUM	LOW	MEDIUM	ALL	MEDIUM	MEDIUM	MEDIUM	MEDIUM		
	11	HIGH	0-1	1-10							10-18	10-18	140	LOW	HIGH	LOW	HIGH	ALL	LARGE	HIGH	HIGH	LARGE		
	12	HIGH	0-3			3-6				6			140	LOW	HIGH	LOW	HIGH	ALL	SMALL-MEDIUM	HIGH	HIGH	MEDIUM		
4	13	LOW		0-12					12-24	29			40	LOW	MEDIUM	LOW	MEDIUM	ALL	LARGE	MEDIUM	MEDIUM	LARGE	V.LARG. SINKHOLE	INGRESS WATER
	14	LOW		0-17					17-31	31	13-31	28-31	40	LOW	HIGH	LOW	HIGH	ALL	V.LARGE	HIGH	HIGH	V.LARGE		
	15	LOW		0-8					8-16	16	8-16		40	LOW	HIGH	LOW	HIGH	ALL	MEDIUM	HIGH	HIGH	MEDIUM		
5	16	GRADIENT	0-6		6-22					22	19-21		20	LOW	MEDIUM	LOW	MEDIUM	ALL	LARGE	MEDIUM	MEDIUM	LARGE	MEDIUM SINKHOLE	INGRESS WATER
	17	GRADIENT	0-5						5-38	38	5-38		20	HIGH	HIGH	HIGH	HIGH	V.LARGE	V.LARGE	HIGH	HIGH	V.LARGE		
	18	GRADIENT	0-6		6-17				17-55	55	17-55		20	HIGH	HIGH	HIGH	HIGH	V.LARGE	V.LARGE	HIGH	HIGH	V.LARGE		
	19	GRADIENT	0-3		3-10				10-30	30	15-30		20	HIGH	HIGH	HIGH	HIGH	V.LARGE	V.LARGE	HIGH	HIGH	V.LARGE		
6	20	GRADIENT	0-3,0			13-40	3-13 (P)			40			140	HIGH	HIGH	HIGH	HIGH	V.LARGE	V.LARGE	HIGH	HIGH	V.LARGE	2 MEDIUM SINKHOLES AND A DOLINE	INGRESS WATER AND DRAWDOWN
	21	GRADIENT	0-4,0			17-50	4-17 (P)			50			140	HIGH	HIGH	HIGH	HIGH	V.LARGE	V.LARGE	HIGH	HIGH	V.LARGE		
	22	GRADIENT	0-4,0			4-63			63-67	67	63-67		140	HIGH	HIGH	HIGH	HIGH	V.LARGE	V.LARGE	HIGH	HIGH	V.LARGE		
	23	GRADIENT	0-6	6-12		12-52			52-57				140	HIGH	HIGH	HIGH	HIGH	V.LARGE	V.LARGE	HIGH	HIGH	V.LARGE		
	24	GRADIENT	0-6	6-15		15-18			18-33	33			140	HIGH	HIGH	HIGH	HIGH	V.LARGE	V.LARGE	HIGH	HIGH	V.LARGE		
7	25	GRADIENT	0-2			2-7			7-15	15	13-15	13-15	27	LOW	HIGH	LOW	HIGH	ALL	LARGE	HIGH	HIGH	LARGE	3 V.LARGE SINKHOLES	DRAWDOWN
	26	GRADIENT	0-3	3-7					7-20	>20	7-20	23-32	27	LOW	HIGH	LOW	HIGH	ALL	LARGE	HIGH	HIGH	LARGE		
	27	GRADIENT	0-1	1-3		3-9			9-25		9-21	22-23	27	LOW	HIGH	LOW	HIGH	ALL	LARGE	HIGH	HIGH	LARGE		
	28	GRADIENT	0-2,0			2-6			6-10	17	10-17	10-17	27	LOW	HIGH	LOW	HIGH	ALL	LARGE	HIGH	HIGH	LARGE		
	29	GRADIENT	0-5						5-18	18	5-8	18-21	27	LOW	HIGH	LOW	HIGH	ALL	LARGE	HIGH	HIGH	LARGE		
	30	GRADIENT	0-8			0-7			8-33	33-36 & >44		36-44	27	LOW	HIGH	LOW	HIGH	ALL	V.LARGE	HIGH	HIGH	V.LARGE		
	31	GRADIENT							7-49	49	7-49		27	HIGH	HIGH	HIGH	HIGH	V.LARGE	V.LARGE	HIGH	HIGH	V.LARGE		
	32	GRADIENT	0-8						8-20	20	8-20		27	LOW	HIGH	LOW	HIGH	LARGE	LARGE	HIGH	HIGH	LARGE		

Table 19: Summary of borehole characteristics (dewatering scenario)- continued.

PART 2

CASE STUDY AREA	BORE HOLE NO.	GRAVITY FEATURE	COLLUVIUM AEOLIAN SANDS ALLUVIUM (M)	CHERT RUBBLE (M)	CHERT RESIDUUM		PRETORIA(P) KAROO(K) ROCKS (M)	INTRU-SIVE	DOLOMITE RESIDUUM INCLUDING WAD/FERR-OAN SOIL	DOLOMITE BEDROCK	POOR DRILLING CONDITIONS/ NSR/RP ETC. (M)	CAVITY (M)	ORIGINAL WATER (M)	RISK CHARACTERISATION				POTENTIAL SINKHOLE DEVELOPMENT SPACE		FINAL CHARACTERISATION AMALGAMATED SCENARIO			ACTUAL RECORDED EVENT	
					FINES PREDOM (M)	FINES SUBORD (M)								DOLINE FORMATION W.L.	DOLINE FORMATION INGRESS WATER	SINKHOLE FORMATION W.L.	SINKHOLE FORMATION INGRESS WATER	WOLDDRWDN	INGRESS WATER	DOLINE	SINKHOLE	DEVEL-OPMENT SPACE	SINKHOLE/DOLINE	CAUSE
8	33		0-16		16-25				25-34	34			49	HIGH	HIGH	HIGH	HIGH	V.LARGE	V.LARGE	HIGH	HIGH	V.LARGE	LARGE SINKHOLE	WATER LEVEL DRAWDOWN. RE-ACTIVATED PALO-SINKHOLE
	34		0-12	12-25	25-28					28			49	HIGH	HIGH	HIGH	HIGH	V.LARGE	V.LARGE	HIGH	HIGH	V.LARGE		
	35		0-24			24-30					19-30		49	HIGH	HIGH	HIGH	HIGH	V.LARGE	V.LARGE	HIGH	HIGH	V.LARGE		
	36		0-28						28-31		28-31		49	HIGH	HIGH	HIGH	HIGH	V.LARGE	V.LARGE	HIGH	HIGH	V.LARGE		
	37		0-23		23-27					27			49	HIGH	HIGH	HIGH	HIGH	V.LARGE	V.LARGE	HIGH	HIGH	V.LARGE		
	38		0-26						26-55	55	26-61		49	HIGH	HIGH	HIGH	HIGH	V.LARGE	V.LARGE	HIGH	HIGH	V.LARGE		
9	39	GRADIENT	0-1						5-22	1-5, >22	8-22		140	LOW	HIGH	LOW	HIGH	ALL	LARGE	HIGH	HIGH	LARGE	2 X MEDIUM SINKHOLES	INGRESS WATER
	40	GRADIENT	0-9		9-24				14-35	35	14-35		140	LOW	HIGH	LOW	HIGH	ALL	V.LARGE	HIGH	HIGH	V.LARGE		
	41	GRADIENT	0-2						2-25		13-25		140	LOW	HIGH	LOW	HIGH	ALL	V.LARGE	HIGH	HIGH	V.LARGE		
	42	GRADIENT	0-1			1-6					6		140	LOW	HIGH	LOW	HIGH	ALL	SMALL	HIGH	HIGH	SMALL		
10	43	GRADIENT	0-7		7-30				30-40	55	36-46		28	HIGH	MEDIUM	HIGH	MEDIUM	V.LARGE	V.LARGE	HIGH	HIGH	V.LARGE	DOLINE	INGRESS WATER?
	44	GRADIENT	0-38						38-62	62	19-68		28	HIGH	HIGH	HIGH	HIGH	V.LARGE	V.LARGE	HIGH	HIGH	V.LARGE		
	45	GRADIENT	0-34						34-68		68		28	HIGH	HIGH	HIGH	HIGH	V.LARGE	V.LARGE	HIGH	HIGH	V.LARGE		
	46	GRADIENT	0-32		32-47				47-60	60	7-60		28	HIGH	HIGH	HIGH	HIGH	V.LARGE	V.LARGE	HIGH	HIGH	V.LARGE		
	47	GRADIENT	0-31		31-48				48-59	59	18-59		28	HIGH	HIGH	HIGH	HIGH	V.LARGE	V.LARGE	HIGH	HIGH	V.LARGE		
	48	GRADIENT	0-29						29-60	60	18-66		28	HIGH	HIGH	HIGH	HIGH	V.LARGE	V.LARGE	HIGH	HIGH	V.LARGE		
11	49		0-2		25-60	2-25							114	MEDIUM	MEDIUM	MEDIUM	MEDIUM	LARGE	LARGE	MEDIUM	MEDIUM	LARGE	MEDIUM SINKHOLE	INGRESS WATER
12	50	HIGH	0-4		4-14				14-18	18			20	LOW	MEDIUM	LOW	MEDIUM	ALL	LARGE	MEDIUM	MEDIUM	LARGE	MEDIUM SINKHOLE	INGRESS WATER
	51	HIGH	0-8						8-20	20	8-20		20	MEDIUM	HIGH	MEDIUM	HIGH	LARGE	LARGE	HIGH	HIGH	LARGE		
	52	HIGH	0-4						4-20	20	16-20		20	MEDIUM	MEDIUM	MEDIUM	MEDIUM	LARGE	LARGE	MEDIUM	MEDIUM	LARGE		
	53	HIGH	0-2		2-7				17-17	17			20	LOW	MEDIUM	MEDIUM	MEDIUM	LARGE	LARGE	MEDIUM	MEDIUM	LARGE		
	54	HIGH	0-4		4-11				11-34		13-34		20	HIGH	HIGH	HIGH	HIGH	LARGE	LARGE	MEDIUM	MEDIUM	LARGE		
	55	HIGH	0-5			5-9			9-19	19			20	LOW	MEDIUM	LOW	MEDIUM							
13	56	GRADIENT	0-5				5-53		53-60	66		60-66	66	LOW	LOW	LOW	LOW	ALL	ALL	LOW	LOW	ALL	2 X DOLINES	WATER LEVEL DRAWDOWN
	57	GRADIENT	0-8				8-35		35-85	85			66	HIGH	LOW	LOW	LOW	ALL	ALL	HIGH	LOW	ALL		
	58	GRADIENT	0-5				5-47		47-85	85			66	HIGH	LOW	LOW	LOW	ALL	ALL	HIGH	LOW	ALL		
14	59	GRADIENT	0-7			68-100	7-68						103	HIGH	LOW	LOW	LOW	ALL	ALL	HIGH	LOW	ALL	2 X DOLINES	WATE LEVEL DRAWDOWN
	60	GRADIENT	0-9				9-90		90-100	100			93	LOW	LOW	LOW	LOW	ALL	ALL	LOW	LOW	ALL		
15	61	LOW	0-11		106-127		11-106							LOW	LOW	LOW	LOW	LOW	ALL	LOW	LOW	ALL	SMALL SINKHOLE	INGRESS WATER
16	62	LOW	0-3				3-36		36-50	50			50	LOW	LOW	LOW	LOW	LOW	ALL	LOW	LOW	ALL	GROUND SETTLEMENT	INGRESS WATER COLLAPSE SETTLEMENT
	63	LOW	0-5		19-31		5-19		31-38	45		38-40	48	LOW	LOW	LOW	LOW	LOW	ALL	LOW	LOW	ALL		

Table 19: Summary of borehole characteristics (dewatering scenario)- continued.

PART 3

CASE STUDY AREA	BORE HOLE NO.	GRAVITY FEATURE	COLLUVIUM AEOLIAN SANDS ALLUVIUM (M)	CHERT RUBBLE (M)	CHERT RESIDUUM		PRETORIA(P) KAROO(K) ROCKS (M)	INTRUSIVE	DOLOMITE RESIDUUM INCLUDING WAD/FERROAN SOIL	DOLOMITE BEDROCK	POOR DRILLING CONDITIONS/ NSR/RP ETC. (M)	CAVITY (M)	ORIGINAL WATER (M)	RISK CHARACTERISATION				POTENTIAL SINKHOLE DEVELOPMENT SPACE		FINAL CHARACTERISATION AMALGAMATED SCENARIO			ACTUAL RECORDED EVENT	
														DOLINE FORMATION		SINKHOLE FORMATION								
					FINES PREDOM (M)	FINES SUBORD (M)								W.L.	INGRESS WATER	W.L.	INGRESS WATER	WOLDDRWDN	INGRESS WATER	DOLINE	SINKHOLE	DEVELOPMENT SPACE	SINKHOLE/DOLINE	CAUSE
17	64	GRADIENT	0-16		27-41					48	16-56	16-27 40-48	31	HIGH	HIGH	HIGH	HIGH	V.LARGE	V.LARGE	HIGH	HIGH	V.LARGE	LARGE SINKHOLE	DRAWDOWN
	65	GRADIENT	0-22		22-61						22-61		31	HIGH	HIGH	HIGH	HIGH	V.LARGE	V.LARGE	HIGH	HIGH	V.LARGE		
	66	GRADIENT	0-13		17-40						17-46		31	HIGH	HIGH	HIGH	HIGH	V.LARGE	V.LARGE	HIGH	HIGH	V.LARGE		
	67	GRADIENT	0-2				2-20		20-42	50	42-56	42-50	31	HIGH	LOW	HIGH	LOW	V.LARGE	ALL	HIGH	HIGH	V.LARGE		
	68	GRADIENT	0-5		25-46		5-25				25-46		31	HIGH	LOW	HIGH	LOW	V.LARGE	ALL	HIGH	HIGH	V.LARGE		
	69	GRADIENT	0-3		3-15				25-28	28			31	LOW	MEDIUM	LOW	MEDIUM	ALL	V.LARGE	MEDIUM	MEDIUM	V.LARGE		
18	70	LOW	0-4		(R)18-99		4-18		99-129, 142-147			129- 142	90	HIGH	HIGH	HIGH	LOW	V.LARGE	V.LARGE	HIGH	HIGH	V.LARGE	DRAMATIC DOLINE	DRAWDOWN
	71	LOW	0-4		(R)25-95		4-25		90-145	145			90	HIGH	HIGH	HIGH	LOW	V.LARGE	V.LARGE	HIGH	HIGH	V.LARGE		
	72	LOW	0-6			62-87	6-62		87-111	111			90	HIGH	LOW	LOW	LOW	ALL	ALL	HIGH	LOW	ALL		
	73	LOW	0-9		45-61	9-45			61-146	146			90	HIGH	HIGH	HIGH	HIGH	V.LARGE	V.LARGE	HIGH	HIGH	V.LARGE		
	74	LOW	0-5			(R)75-123	5-75			123			90	LOW	LOW	LOW	LOW	ALL	ALL	LOW	LOW	ALL		
	75	LOW	0-4			(R)70-91	4-70		97-109	109		91-97	90	HIGH	LOW	LOW	LOW	ALL	ALL	HIGH	LOW	ALL		
19	76	HIGH	0-4		4-9				10-30	30	17-29		20	HIGH	MEDIUM	HIGH	MEDIUM	V.LARGE	V.LARGE	HIGH	MEDIUM	V.LARGE	MEDIUM SINKHOLE	DRAWDOWN
	77	HIGH	0-5	8-12						12			20	LOW	MEDIUM	LOW	MEDIUM	LARGE	LARGE	MEDIUM	MEDIUM	LARGE		
	78	HIGH	0-6	6-8	17-25				8-17	25			20	HIGH	MEDIUM	HIGH	MEDIUM	V.LARGE	V.LARGE	HIGH	HIGH	V.LARGE		
	79	HIGH	0-4	4-9					9-24	24	12-20		20	HIGH	HIGH	HIGH	HIGH	V.LARGE	V.LARGE	HIGH	HIGH	V.LARGE		
	80	HIGH	0-2	4-7						7			20	LOW	MEDIUM	LOW	MEDIUM	MEDIUM	MEDIUM	MEDIUM	MEDIUM	MEDIUM		
20	81	GRADIENT	0-2		4-33				33-87				130	LOW	MEDIUM	LOW	MEDIUM	V.LARGE	V.LARGE	MEDIUM	MEDIUM	V.LARGE	V.LARGE SINKHOLE	INGRESS WATER
	82	GRADIENT	0-2		2-25				25-75	75	60-74		130	LOW	HIGH	LOW	HIGH	V.LARGE	V.LARGE	HIGH	HIGH	V.LARGE		
	83	GRADIENT	0-5		5-45				45-85	85	51-85		130	LOW	HIGH	LOW	HIGH	LOW	V.LARGE	HIGH	HIGH	V.LARGE		
	84	GRADIENT	0-5		5-47				47-116	116	47-116		130	LOW	HIGH	LOW	HIGH	LOW	V.LARGE	HIGH	HIGH	V.LARGE		
	85	GRADIENT	0-2		2-72				72-92	92	61-92		130	LOW	HIGH	LOW	HIGH	LOW	V.LARGE	HIGH	HIGH	V.LARGE		

As no reliable geophysical tool is available to determine the presence of cavities above and in the dolomite bedrock, it is assumed that receptacles in fact exist in the rock and that disseminated receptacles may be present in certain overburden materials (See Chapter 6).

Twenty case study areas embracing twenty eight actual ground movement events and eighty five borehole profiles are reviewed in Table 19. The boreholes utilised for characterisation purposes are evaluated in the context of the geological and geomorphological setting in which they are placed. A review of the correlation between the stability characterisations and the actual recorded ground movement events reveals that on average, 1 in 14 events exceed expectation. Alternatively, 7% of events can be expected to exceed prediction. The greater degree of accuracy in the characterisation of events in the context of this scenario is most likely attributable to two factors, namely:

- The West Rand area, which is being subjected to dewatering is generally characterised by a deep karstification. The gravity survey data and borehole information tend to indicate the existence of deep paleokarst valleys. Consequently the potential development space may be larger.

- A more conservative approach may automatically be adopted in the application of the methodology in view of the historical data pertaining to areas subjected to dewatering. Experience indicates that the dewatering process may induce the most catastrophic events.

In order to display the application of the methodology to the dewatering scenario, the procedure of the characterisation of several interesting profiles will be discussed below:

- **Borehole 21, Case Study Area 6, Table 19, Part 1.**

This subsurface profile is characterised by the presence of 3m of colluvium overlying 13m of Pretoria Group shales which in turn are underlain by 33m of chert residuum. Dolomite bedrock is noted at a depth of 50m. The case study area is defined by a gravity gradient. Receptacles are assumed to be located within the dolomite bedrock. The original waterlevel is noted as being well within the dolomite bedrock (i.e., 140m below ground level). Consequently, during the dewatering, process the drawdown of the waterlevel will take place "within" the dolomite bedrock. Normally this drawdown process would not have an influence on stability and the risk of mobilisation of the blanketing layer would be assumed to be low. A similar deduction is made with respect to mobilising agencies such as ingress water.

Historical data serve however to moderate this assessment. Many spectacular ground movement events have been induced in similar geological settings during the dewatering process. Fault zones, particularly thrust faults, have proven to be hazardous areas in such particular geological settings. These zones provide preferential drainage paths for downward seepage of ingress water. Openings within the actual fault zone often act as receptacles for any mobilised soil material. The fault may alternatively act as a conduit feeding mobilised material to receptacles at a lower depth. In a highly weathered fault zone the dewatering process may generate a ravelling process within a conduit connecting the surface to the deeper lying receptacles in the fault zone or in the dolomite. Consequently, these fault zones must be characterised as reflecting a high risk of mobilisation. In the case of the area denoted as "case study area 6" uncertainty concerning the location of faults leads to a conservative characterisation of the area as reflecting a high risk of doline and very large sinkhole formation.

- Borehole 36, Case Study Area 8, Table 19, Part 2.

The subsurface profile of this gravity low feature, as indicated by Borehole 36, is noted to typically consist of 28m of aeolian sands overlying 4m of clayey silt (wad) with dolomite bedrock at 31m. The original waterlevel is located at 29m below surface. It is apparent that the boreholes drilled have encountered a paleosinkhole.

The potential receptacles are assumed to be present below the throat of the paleo-sinkhole or at shallower depth in the peripheral regions of the feature. Experience indicates that a dramatic lowering of the water level may induce re-activation of the paleo-sinkhole. In addition the nature of the dolomitic environment surrounding the paleo-sinkhole may be characterised by very poor subsurface conditions. The mobilisation potential of the blanketing layer in a dewatering scenario is assessed as "high risk". The mobilising agencies may be operative as follows:

i) The lowering of the waterlevel usually leads to a change in the moisture regime prevalent in the soil material constituting the paleo-sinkhole fill. The change can induce a loss in shear strength and initiate arching. Soil material will ravel into the paleo-receptacle as the arch migrates up towards the ground surface through the aeolian sand. Alternatively consolidation settlement may accompany dewatering.

ii) The blanketing layer is essentially constituted by the aeolian sands. Experience indicates that these materials may have a moderate to good internal drainage. Consequently ingress water may lead to subsurface erosion and mobilisation of the blanketing layer.

These processes may be operative separately or simultaneously in the profile. In view of the nature of the subsurface conditions, this profile is characterised as reflecting a high risk of doline and very large sinkhole formation.

- Borehole 57, Case Study Area 13, Table 19, Part 2.

Borehole 57 has a typical subsurface profile in this case study area, consisting of 8m of colluvium overlying 27m of Karoo rocks and 50m of residual dolomite. Dolomite bedrock is noted at a depth of 85m below surface. The original water level is above dolomite bedrock at 66m below surface. Disseminated receptacles may be present in the bedrock. The blanketing layer covering the disseminated receptacles essentially consists of the colluvium and Karoo rocks while in the case of the receptacles in the dolomite, this layer consists of colluvium, Karoo rocks and the dolomite residuum. In a dewatering scenario, a lowering of the water level may result in the mobilisation of a portion of this blanketing layer. A change in the moisture regime in the dolomite residuum may, given the conditions proposed by Jennings et al (1965), give rise to void formation and migration. The substantial thickness of Karoo rocks is viewed as competent, capable of spanning such developing voids. Consequently, in this respect the mobilisation potential of the blanketing layer is regarded as low. Dewatering may result in large scale consolidation settlement. If this settlement is manifest laterally over a large area, the Karoo rocks may yield, resulting in doline formation at surface. Experience indicates that the Karoo rocks have poor internal drainage characteristics, essentially acting as aquitards, retarding water ingress and preventing subsurface erosion. It is, therefore, concluded that the blanketing layer has a low mobilisation potential as regards sinkhole formation caused by ingress water or waterlevel drawdown. Doline formation (i.e. limited mobilisation of the blanketing layer) is regarded as "high risk".

Consequently in a dewatering scenario the subsurface conditions in case study area 13 is regarded as reflecting a high risk of doline formation and a low risk of sinkhole (all) formation.

- **Borehole 80, Case Study Area 19, Table 19, Part 3.**

This case study area is located on a gravity high, hence raising the expectation that the dolomite bedrock occurs at shallow depth. Borehole 80 confirms this expectation, indicating that bedrock occurs at 7m. Colluvial soil material is noted to occur from ground surface to a depth of two metres and chert rubble from 4m to 7m. Receptacles are assumed to be present within the bedrock and disseminated receptacles within the chert rubble. The original water level is noted as 20m below ground surface.

The waterlevel is well within bedrock and consequently, drawdown is not anticipated to have any effect on stability. Hence the mobilisation potential of the blanketing layer is characterised as "low risk" (Table 19). Experience indicates that the colluvium material and chert rubble constituting the blanketing layer tend to have a good internal drainage. A multitude of potential flow paths exist in these permeable materials permitting percolating water from a leaking service etc., to achieve the critical flow velocity required to overcome the hydrodynamic stability of the particles. Subsurface erosion results. If sustained ingress of water occurs and if the receptacles are of adequate volume, a sinkhole of "medium" size may form. If the ingress of water should be terminated or conduits to the receptacles choked, a doline may result as described in chapter 2.5. The blanketing layer is consequently characterised as reflecting a "medium risk" of mobilisation (Table 19).

Amalgamation of the various characterisations discussed above leads to the characterisation of the subsurface conditions represented in borehole 80 as reflecting a medium risk of doline and medium size sinkhole formation (Table 19).

It is important to bear in mind that the characterisation of the individual boreholes is followed by a process of pooling all the individual borehole characterisations and formulating a composite expression of the stability. This process must take cognizance of historical data.

8. CONCLUSIONS:

This document has attempted to give broad and, consequently, simplified background information pertinent to understanding the significance for characterising the stability of dolomitic land prior to development. A single framework of reference for the execution of stability evaluations has been proposed. This proposal was developed after reviewing existing classification systems, investigation procedures, stability investigation reports and following extensive consultation with engineering geologists, geotechnical and civil engineers, geohydrologists, hydrologists and town and regional planners.

The proposed approach has been entitled "the method of scenario supposition" and essentially provides a general set of factors to be utilised as a check list defining a deductive process and culminating in a stability characterisation. The factors for the characterisation of the risk of doline and sinkhole formation have been defined as has the associated terminology.

This method of characterisation culminates in the expression of the stability in terms of the risk of doline and sinkhole formation. Proposals have been made concerning appropriate development in relation to the risk.

The following points are considered to be significant:

- This document is concluded with acceptance of the principle that development on dolomite is feasible, but it is vital that appropriate development is considered in relation to the risk characterisation. It is essential that regional and local planning take the potential risk characterisation of the dolomitic land into account in order to ensure that an effective and optimum land allocation strategy is developed and applied.

- It is imperative that, as pressure mounts for dolomite land to be made available for residential development, particularly low cost, high density housing, the standard of investigations and precautionary measures are neither ignored nor relaxed.

The public must have the confidence that there are no hidden dangers attached to the land it has purchased once a township is proclaimed.

- In view of the statement made above, the standard of stability investigations has increasingly caused concern as has also the lack of standardisation in methodology, terminology and investigation procedure. Of great concern is the level of awareness pertaining to the dolomite issue amongst planners and engineers responsible for the design of townships and the implementation of appropriate precautionary measures.

The procurement of stability reports is, unfortunately, sometimes viewed merely as an obstacle to be overcome in terms of statutory requirements.

- The method of scenario supposition culminates in the characterisation of the stability of the site in terms of the risk of doline and certain size of sinkholes forming. It must be emphasised that this methodology is aimed at developing a "perception" of the stability of the site. The highly variable nature of the dolomite karst environment combined with the "course" nature of the investigation techniques utilised, necessitates that the results obtained and perceptions formulated are tempered with circumspection.

Urban development normally results in disturbance of the metastable conditions prevalent in the dolomite environment. Consequently, the basic design of the township is a key element in the overall strategy to minimise the impact of the proposed development on the environment. The particular type of development selected in relation to the risk is critical to the safe, successful and long term viability of a project. It is imperative that the engineering geologist/geotechnical engineer responsible for the stability characterisation of the site is involved in all the stages of a development project.

This involvement includes such aspects as the certification of the township outlay, (Chapter 3, section 3.3) and monitoring of service design an installation.

- This document is completed at a time when approximately twenty five dolomitic stability investigation reports have been completed by various consultants utilising this methodology. It may prove of value to ascertain the deviation in risk characterisations assigned to the same geological setting by various experts. It must be reiterated that the results of the application of this methodology is largely dependent on the experience of the evaluator.

- Four categories of sinkhole sizes are suggested in this methodology and in the terminology. Perhaps this four fold classification is too sensitive. Consideration should be given to reducing the size categories to three namely, small, medium and large sinkholes. This matter has been discussed at length with fellow engineering geologists and engineers and the consensus is that the categories remain unchanged for a test period. A follow-up research project and paper can perhaps deal with this matter once additional experience and data have been gathered permitting back analysis.

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10. REFERENCES

Brink, A.B.A. 1979. Engineering Geology of Southern Africa. Vol .1, Building Publications, Pretoria.

Bulton, A., 1973. A Regional Study of the Stratigraphy and Development of the Transvaal Basin in the Eastern and Northern Transvaal. Unpublished Ph.D. Thesis, Univ. of Witwatersrand.

Button, A., 1973. A regional stratigraphy and development of the Transvaal basin in the eastern and northern Transvaal. Unpublished Ph.D Thesis, University of Witwatersrand.

Buttrick, D.B., 1986. Wad and Ferroan Soil Developed in the Dolomitic Area South of Pretoria. Unpublished MSc Thesis, Univ. of Pretoria.

Buttrick, D.B., 1987. The Role of Wad in Stability Evaluation. Seminar on the Engineering Geology Evaluation of Sites on Dolomite. S.A. Geological Survey and the Univ. of Pretoria. 7 September 1987. p.54-63.

Buttrick, D.B., 1988. Parameters and Standardised Terminology for Sinkhole Size and Risk in Stability Evaluation: Tentative Proposals. Ground Profile No. 58.

Buttrick, D.B., 1988. Reporting Requirements for Dolomite Stability Investigations. The Perspective of the Unit for Applied Studies on Dolomite, S.A. Geological Survey. Ground Profile No. 57, January 1989.

Changuion, J.P., 1981. Ontwikkeling en Beplanning van Dolomietgebiede Gesien Uit die Eienaar of Gronverbruiker se Oogpunt. Seminar on the Engineering Geology of Dolomite Areas. Univ. of Pretoria 26-27, November 1981. p.52-56.

Coon, R.F. and Merrit, Predicting insitu modules of deformation using A.H., 1978 quality indexes. American Std. Test materials STP 477.

Cosser, E., 1989. Update 8, South African Institute of Race Relations March 1989 - July 1989.

De Beer, J.H., 1981. Evaluation of dolomite areas. Seminar on the engineering geology of dolomite areas, University of Pretoria, 26-27 November 1981.

Eriksson, K.A.,Truswell, J.F., 1974. Stratotypes from the Malmani Sub Group North-West of Johannesburg, South Africa. Trans. Geol. Soc. South Africa. Volume 77, Number 3 p.211-222.

Far West Rand Dolomitic Water Association, - Annual Reports 1964-1989.

Hartopp, P.G., 1981. Interpretation and comparison of remote sensing methods in determining the engineering geological characteristics of dolomite areas. Seminar on the engineering geology of dolomite areas, University of Pretoria, 26-27 November 1981.

Jennings, J.E., Brink, A.B.A., Louw, A. Gowan, G.D., 1965. Sinkholes and Subsidences in the Transvaal Dolomites of South Africa. Proceedings of the Sixth International Conference on Soil Mechanics and Foundation Engineering, Canada, Volume 1, p 316-319.

Jones, D.H., 1981. The use of telescopic benchmarks for monitoring geotechnically unstable areas. Seminar on the engineering geology of dolomite areas. University of Pretoria. 26-27 November 1981.

Jones, D.H., 1986. Evaluation of potential ground instability of Karoo outliers associated with dolomite in the Vaal Triangle. Seminar on the evaluation of dolomite areas. University of Pretoria, 24 May 1986.

Kleywegt, R., 1987. Keynote address. Seminar on the engineering geological evaluation of sites on dolomite. S A Geological Survey, Pretoria 7 September 1987.

Mashabela, H., 1988. Townships of the P.W.V. South African Institute of race Relations.

National Building Research Institute of the CSIR, 1984. A Technical Guide to Good House Construction. Assoc. of Building Societies. ISBN 0 7988 1168 4.

Roux, P., 1984. Geotegniese Ondersoeke vir Dorpsontwikkeling in Dolomiet Gebiede. Unpublished PhD. Thesis, Univ. of Pretoria.

Schoning, W. and A'Bear, A., 1987. A Critique of Classification Systems Applied to Dolomite Areas. Seminar on the Engineering Geological Evaluation of Sites on Dolomite. S.A. Geological Survey and Univ. of Pretoria. Pretoria 7 September 1987.

Schoning, W., 1990. Verspreiding van singate en versakkings in die dolomiet - gebiede suid van Pretoria. Unpublished Msc thesis University of Pretoria. p. 120-125.

South African Committee for Stratigraphy (SACS), 1980. Stratigraphy of South Africa. Part 1. (Comp. L.E. Kent). Lithostratigraphy of the Republic of South Africa, South West Africa, Namibia and the Republics of Bophuthatswana, Transkei and Venda: Handb. Geol. Surveys S. Afr., 8.

Stephan, L.A., 1975. Stability prediction from borehole logs of dolomite areas. Unpublished report, S.A. Geological Survey.

Van Rooy, J.L. 1984. Sonering van 'n Dolomietgebied Suid van Pretoria met Behulp van 'n Meervoudige - Factor Klassifikasiestelsel. Unpublished M.Sc. Thesis, Univ. of Pretoria.

Van Schalkwyk, A., Ontwikkelingspatroon en Risiko Evaluasie in 1991. Dolomietgebiede. Seminar on the Engineering Geology of Dolomite Univ. of Pretoria 26-27 November 1981. p.9-24.

Venter, I.S., 1981. Evaluasie van Dolomietgebiede - 'n Klassifikasie-benadering. Seminar on the Engineering Geology of Dolomite Areas. Univ. of Pretoria, 26-27. November 1981. p.272-284.

Wagener, F. Von M., 1982. Engineering Construction on Dolomite. Ph.D Thesis Univ. of Natal.

Weaver, J.M., 1979. Geological Investigation Conducted at T.E.K. Base Single Quarters Verwoerdburg. Report Number J90/1 for Dept. Community Development, May 1979.

Whitten, G.G. and Brooks, J.R., 1972. A Dictionary of Geology. Penguin Books Ltd., Middlesex, England.

Wrench, RP., 1984. Plate load tests for the measurement of modules and bearing capacity of gravels. Draft paper presented to the S A Institute of Civil Engineers.